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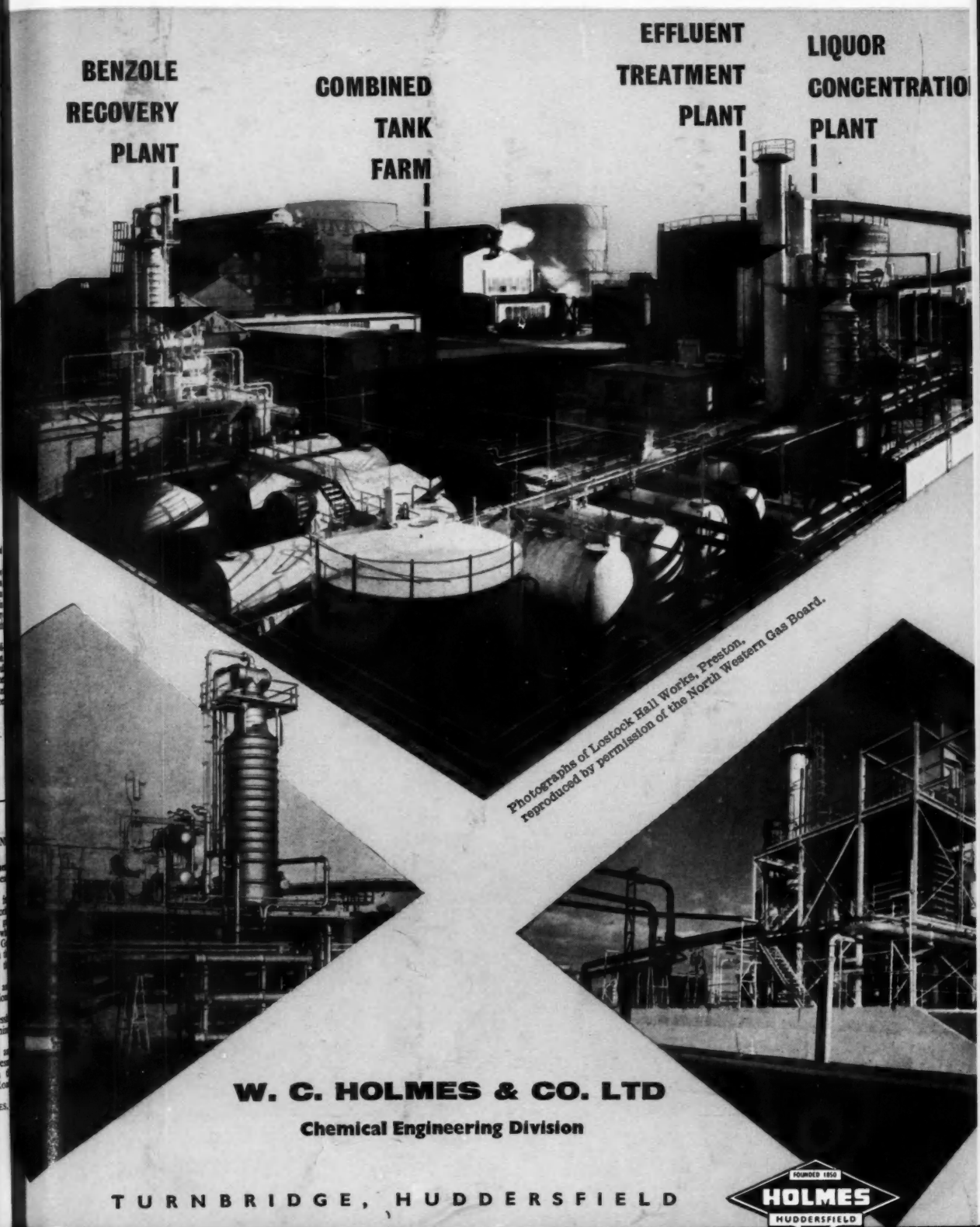
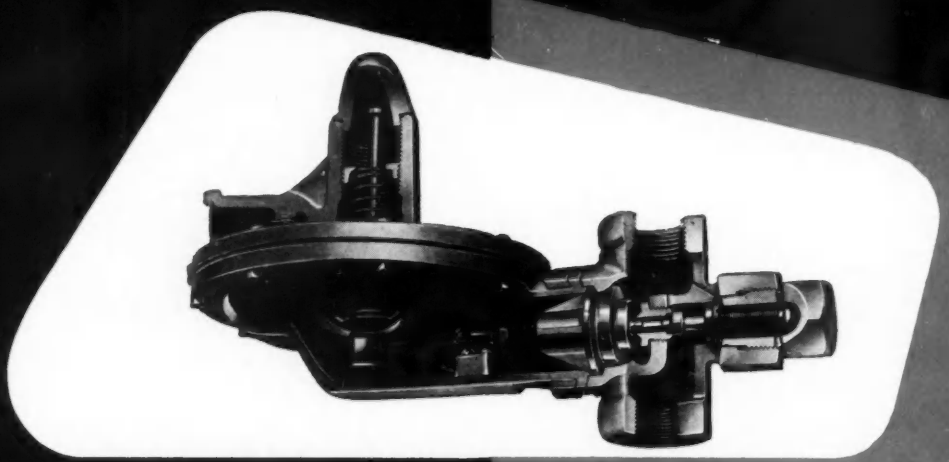
ENGINEERING

Gas Journal

VOL. 295. 110th YEAR. LONDON, SEPTEMBER 10, 1958 No 4965 PRICE 1/6





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Gas Journal

VOL. 295 NO. 4965 SEPTEMBER 10, 1958

110TH YEAR

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Published by Walter King Limited,
11, Bolt Court, Fleet St., London, E.C.4

Telephone: FLEet Street 2236-7 Telegrams:- Gasking, Fleet.

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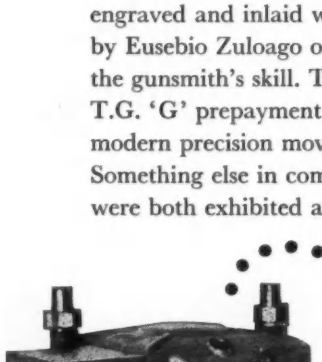
something in common

They remind one of different worlds, the Spanish forged iron pistol of 1850 and the modern T.G. meter. Yet, they have something in common — both are the products of true craftsmanship. The pistol delicately engraved and inlaid with damascene, designed and made by Eusebio Zuloago of Madrid, is presented as a fine example of the gunsmith's skill. The T.G. meter epitomizes craftsmanship and the T.G. 'G' prepayment mechanism is accepted as the most modern precision movement on the market.
Something else in common, this Spanish pistol and a T.G. meter were both exhibited at the Great Exhibition of 1851.



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1958

Gas Journal

VOLUME 295. No. 4965 SEPTEMBER 10, 1958. 110th YEAR

Symposium on Combustion

THE arrival in London recently of 500 physical chemists from all over the world to attend the seventh international symposium on combustion, gives some idea how very important this branch of chemistry has become. Included among them were those whose work contributed to the launching of the Soviet and American satellites.

The meetings of the symposium took place mainly at Oxford but the inaugural address by Lord Brabazon of Tara was given at the Royal Institution and was followed by addresses by Sir Cyril Hinchelwood, Sir Alfred Egerton and Dr. Bernard Lewis of the United States. The choice of the Royal Institution was a happy one in that the early work on the famous safety lamp had been carried out there by Sir Humphrey Davy and Faraday, and famous scientists working in the field of heat and energy, such as Count Rumford and Dewar, had lectured in the hall in which the delegates met. Oxford, too, has strong connections with combustion research. Early workers in this field include those working with Dixon in the cellars of Balliol College and Baker, who was one of the first to investigate the inhibition of the hydrogen-oxygen reaction under conditions of extreme dryness. In more recent years, the work on the mechanism of this reaction by Sir Cyril Hinchelwood, Dr. Lee's Professor of Chemistry at Oxford, is well known.

The symposium was organised jointly by the Combustion Institute of the United States and the Institute of Fuel. The delegates came from all over Europe, including the Soviet Union and Hungary, Australia, Canada and Japan, as well as Great Britain and the United States. They included engineers as well as chemists, who were thus able to discuss the latest advances in their special fields.

The scope of the papers read at the technical meetings—there were 122 papers in all—showed how important this branch of science has become. The subjects covered included, among others, the properties of detonation waves, ignition and limits of inflammability, the mechanism of combustion reactions and turbulence in flames.

Combustion in some form or another has become very much part of our every day lives and it is, therefore, interesting to look back on the state of our knowledge of it 100 years ago. Physical chemistry was then in its infancy and was only just emerging as a separate branch of study. The old conception of heat as a kind of invisible fluid capable of flowing from one body to another and known as 'caloric' by Lavoisier in the eighteenth century, had only just been superseded by Joule's work on the mechanical equivalent of heat. The quantitative relationship had only recently been discovered between the chemical action of oxidation and the production of heat, which finally led to the established definition of combustion as any chemical reaction producing both light and heat.

In the '50's of the last century when science began to make such great advances, Thomson, afterwards Lord Kelvin, began his researches which led to the enunciation of the laws of thermodynamics. Once the quantitative relationships between energy and heat had been proved, work could go forward on the connection between them and the production of heat by combustion. This may be said to have been established by 1860. As more exact measurement became possible and more accurate and less clumsy apparatus was built, investigations into the mechanics of flame production and its propagation could be made. This knowledge and the use of hydrocarbon gases and petroleum distillates which were becoming available towards the end of the century, made possible the building of the internal combustion engine.

This was a great step forward but there was still the need for a greater knowledge of flame characteristics from gaseous and liquid fuels to improve the working efficiency of the engines then in use. Some 30 years ago investigations were carried out into flame propagation and flame speeds, which showed that propagation was independent of the material of which the tube was made and its speed increased at constant acceleration until very high detonation speeds were reached. The importance of combustion today is in the successful use of new fuels and the use of familiar fuels in unusual forms. This applies, principally, to rockets and guided missiles. The use of liquefied and solidified hydrocarbon fuels with solid oxygen appears to be making progress. The use of hydrazine as a fuel, on which a

paper was read at the symposium, is a comparatively new development.

For the gas industry the chief interest in combustion lies in its effect on gas utilisation. This aspect is perhaps of almost greater importance than the efficient use of heating gas in retort settings. Much work has been done in recent years in investigating how the combustion characteristics of town gas of differing composition is affected in burners of different designs. This is most important where constant heat outputs must be maintained. Difficulties from changes in gas composition causing the lifting of the flame have also to be met. With these points in mind, we are publishing two papers read at the symposium; one, 'The Vertical Tube Reactor—a Tool for the Study of Flame Processes,' and the other 'The Effect of Adding Auxiliary Gas on Turbulent Blow-off Stability.'

Loss to Gas Industry

THE Continental gas industry has always been of interest to the British gas industry although it came into being later and has always remained on a much smaller scale. In Europe even today it is the German gas industry that most nearly approaches our own in extent though its developments have been on different lines. The concentration of production in coke ovens in the industrial centres and the sale of coke oven gas through long distance transmission mains to the municipally owned local networks is the general practice rather than a system resembling our own.

The prevalence of brown coals and lignites, neither of which occur in this country, has encouraged investigation into high pressure processes which have only recently assumed importance here. This almost certainly accounts for the many developments which have come from the continent in connection with these types of gas-making plant, and we read with regret in a recent issue of *Das Gas-und Wasserfach* of the death of two prominent members of the Continental gas industry both of whom had contributed much to knowledge in this field, one an Austrian and the other a German. Both held technical degrees (Dipl. Eng. Dr. Tech. and Dr. Eng. Dr. Tech.); the one was an engineer and the other a professor.

The engineer, Carl Marischka, was born in Vienna in 1877 and after studying at the Technical High School there, graduated in 1900. In 1904, after holding positions in other industries, he joined the gas industry and was appointed to the Vienna gasworks.

About this time, plans were put in hand for the rebuilding of the Leopoldau works and the founding of the planning and building department to which Carl Marischka was appointed, together with Franz Menzel and Franz Bössner, two well known gas engineers at the time. As the result of the work done in this department, the regenerative heating of horizontal chamber ovens was introduced at both the Vienna works, Leopoldau and Simmering, in 1910. The oven heating was by cold, purified producer gas from central producers of the steam boiler type. In the design of these producers, Carl Marischka put forward several new ideas of great practical value. In 1912, he was appointed to the management of the Leopoldau works, a post he held until his retirement in 1941. During his career he was responsible for a number of developments of interest. In 1910 he introduced reinforced concrete purifier boxes and later designed a revolving shutter gas meter. He was also responsible for working out a process of removing the poisonous constituents from town gas.

His reputation as a gas engineer grew rapidly so that he was soon recognised as an international authority on gas engineering and in demand as a consultant. The Technical High School at Vienna appointed him as a member of the Examination Commission of Fuel and Gas Technology and in 1952 the Austrian Institute of Gas and Water Engineers made him an honorary member. Since the war he had been acting as the representative in Austria of Heinrich Koppers, G.m.b.H., of Essen.

The Professor, Ernst Terres, was born in Metz in 1887 but spent most of his youth in Luxemburg where he received a bilingual education. After studying at Heidelburg and Graz, he graduated from the Technical High School (Fridericiana) in Karlsruhe in 1909, where he was later to be appointed a lecturer about the time of the outbreak of the first world war. His earliest work was as a physical chemist under Haber, but in order to broaden his knowledge he also studied organic chemistry under Roland Scholl, with particular attention to dyestuffs. Later he worked in fuel chemistry, studying combustion products from gas flames and internal combustion engines. This led to an investigation into the use of benzole as a fuel for such engines and an interest in the six-stroke engine.

In 1911 he was engaged in the study of new methods of carbonisation and heat recovery by regenerators and recuperators. Terre's work was repeatedly interrupted by periods of work in industry. By 1918 he had become Professor Extraordinary at Karlsruhe, which was followed by a period in industry as a technical Director of the Didier Company, during which time he carried out a great deal of work on a theoretical basis on the measurement and calculation of coking temperatures, coking properties and allied subjects. In 1923 he was appointed Honorary Professor of the Technical High School of Berlin—Charlottenburg. After leaving the Didier Company in 1925 he became Professor at the Technical High School at Brunswick followed by a regular Professorship in technical and mining chemistry at Berlin-Charlottenburg.

It was not long before Terres was to return to industry. This he did for 15 years from 1933 to 1948 as Manager of the Edeleanu Company, of Berlin, and for a few years after the war as an adviser to an English oil company. In 1948 he returned to academic life as Professor of Gas Technology and Fuel Economy at Karlsruhe and later as Director of both the Gas Institute and the newly formed Engler-Bunte Institute for Mineral Oil and Coal Development.

Ernst Terres received many honours, among which was to be made Rector of Brunswick, Charlottenburg and Karlsruhe Technical High Schools. In 1952, an Honorary Doctorate of the Vienna Technical High School was conferred upon him and in 1953 he received the Carl Bunte medal. He retired in 1957 in his seventieth year.

Personal

MR. C. H. CHESTER, Chairman of the South Western Gas Board, recently presented long service certificates to DR. ARTHUR MARSDEN, the Board's Area Scientist, seen in the centre of the accompanying illustration, and MR. W. F. DIBBLE (right), the Board's Accountancy Assistant in Charge, at Barnstaple.

Dr. Marsden retires at the end of September, after 53 years' service in the gas industry. He was trained under the late J. FERGUSON BELL, and for several years was Chief Assistant Chemist to the Derby Gas Light and Coke Company. In 1913 he became Chief Chemist to the Bath Gas Company, and in 1919 was appointed by the Bristol Gas Company to the chemical staff, and later to the engineering staff. From 1927 to vesting date Dr. Marsden was Chief Chemist to the Bristol Gas Company, and then became Area Scientist to the Board, which post he has since occupied.

Mr. Dibble, who retired on September 7, joined the Barnstaple Gas Company in 1906, and in 1919 became Assistant Manager. He occupied this post until 1938, when he was appointed Secretary to the Barnstaple Gas Company; he continued in that capacity until Vesting Date, when he became subdivisional accountant to the South Western Gas Board at Barnstaple. In 1954, Mr. Dibble was appointed Accountancy Assistant in Charge at Barnstaple, which post he occupied until his retirement.

MR. GEORGE S. DUNSTER, Office Controller of the Reading Region of the Southern Gas Board, has retired after 47 years with the Board and the old Reading Gas Company, of which he was once Secretary.

MR. G. B. TAYLOR, who joined the Stockton-on-Tees firm of Ashmore Benson Pease and Co., Ltd., 30 years ago as an apprentice, has been appointed Sales Manager for the Company's Works Division. MR. H. H. FOSTER has been appointed Works Manager.

MR. HUGO FALK, Chairman and Managing Director of Falk, Stadelmann & Co., Ltd., sails tomorrow for the United States in connection with the Company's American interests.

GAS WORKERS TO GET MORE PAY

ABOUT 100,000 workers in the gas industry are to get a pay increase of 2d. an hour back-dated to August 1. This decision was reached by the special arbitration board set up by Minister of Labour, Mr. Iain Macleod.

Gas workers had been offered an increase of 1½d. an hour by the Gas Council, and strike action had been suggested as a means of securing a bigger increase. The total cost of the arbitration award will be about £2 mill.

Obituary

MR. W. N. MCCANN, Manager of the Manchester Branch of the Silvertown Rubber Co., Ltd., has died suddenly. Mr. McCann joined the Company in 1931 and for some years worked in the Liverpool area. Subsequently as Manchester Branch Manager he became well known to a wide circle of friends and customers throughout the North of England.

Diary

September 12.—SOCIETY OF INSTRUMENT TECHNOLOGY (MIDLAND SECTION): Regent House, St. Phillips Place, Colmore Row, Birmingham 3. 'Fuel Efficiency and Smoke Abatement,' by C. A. J. Plummer. 7 p.m.

September 12.—SCOTTISH ASSOCIATION OF GAS MANAGERS: Civic Theatre, Ayr. Annual General Meeting.

September 16.—INCORPORATED PLANT ENGINEERS (BIRMINGHAM BRANCH): Hotel Leofric, Coventry. 'Clean Air,' by R. Williams, Chief Public Health Officer, Coventry.

September 17.—SOUTH WESTERN G.C.C.: Taunton. Meeting at 11 a.m.

September 18. — INCORPORATED PLANT ENGINEERS (BLACKBURN BRANCH): White Bull Hotel, Blackburn. 'Recent Advances Towards Thermonuclear Power (Sceptre and Zeta),' by J. E. Read. Joint meeting with the Institute of Fuel. 7.30 p.m.

September 20. — SCOTTISH WESTERN JUNIORS. President's Day. Joint visit with East of Scotland Juniors to new plant at Provan gasworks. 2.30 p.m.

September 22. — WEST MIDLANDS G.C.C.: Edmund Street, Birmingham 3. Meeting at 2.30 p.m.

September 24. — I.G.E. (NORTH OF ENGLAND SECTION): Yoden Road Common Room, Peterlee, Co. Durham. Paper on 'The New Towns of County Durham—Their Economic and Social Contribution,' by Mr. A. V. Williams. 2.30 p.m.

George Wilson Gas Meters Ltd.

MR. W. D. WILSON, Chairman of the Coventry firm of George Wilson Gas Meters, Ltd., states in his annual review, which is now being circulated among the shareholders, that after suffering losses for two years running the firm is to contract its production facilities and to concentrate on improving efficiency.

The review and the annual accounts will be presented at the annual meeting on September 26. Consolidated accounts for the year ended March 31, 1958, show a Group loss of £6,627. The previous year the loss was £2,445.

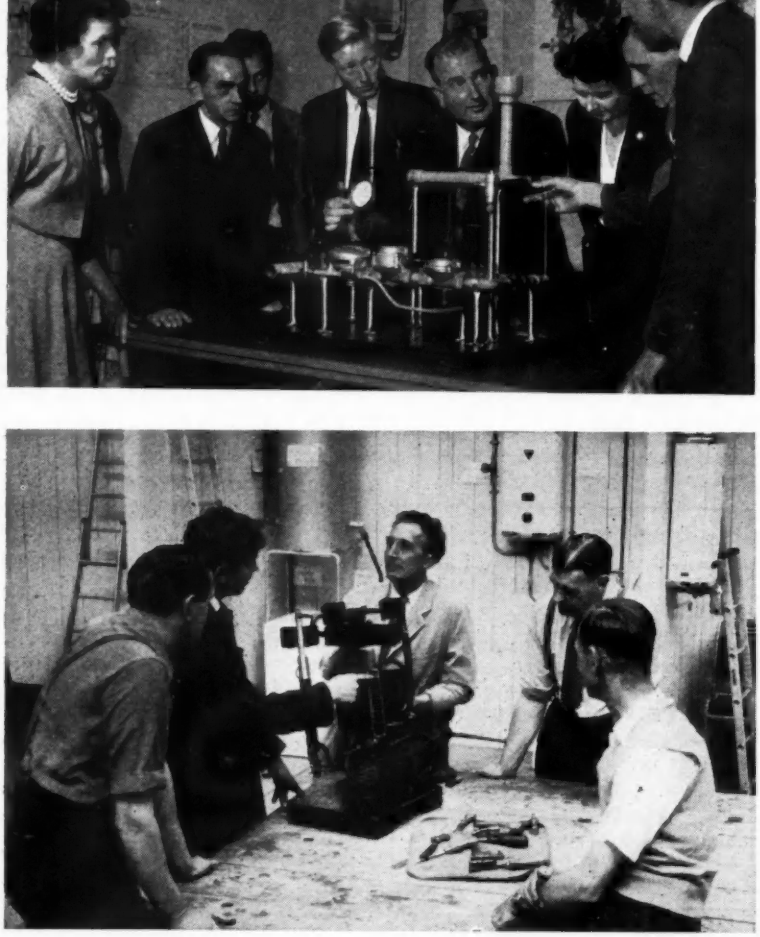
Announcing the Board's decision to contract production facilities, Mr. Wilson states that the first necessity is to reduce the costs to a minimum. With this in view the declared policy of diversification has been deferred for the time being. As an immediate step in reducing expenses the firm recently relinquished the additional factory at Jarrow, Durham, which was taken on lease in 1957.

Mr. Wilson adds: 'This and other steps which are being taken by the Board will, it is hoped, enable the Company to stabilise its economy on a new level and when that object has been achieved your Directors visualise the revival of a gradual process of development and expansion into other lines of production.

He reports that the subsidiary Company, Radiant Heating, Ltd., makers of gas space heaters and other appliances, suffered a rather severe decline in trading, and on top of that was involved in a costly legal action which more than accounted for the loss of £3,000.

Mr. Wilson points out that the dissolution of the Gas Meter Manufacturers' Conference in the latter part of 1957 resulted in keener competition and substantial reduction in selling prices.

TRAINING AND EDUCATION WITH

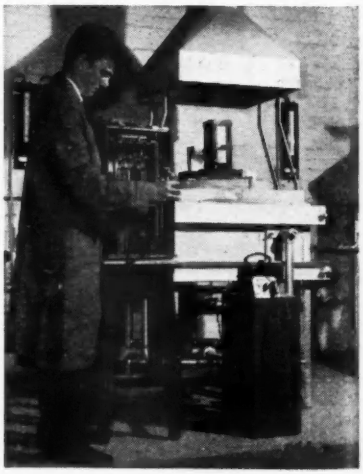


Individual Skill —Efficiency Are

JUST issued is a report by the South Eastern Gas Board on their achievements in the field of training and education during the year ended March 31, 1958.

With many illustrations, some of which are reproduced on these pages, it tells a story of great effort and enthusiasm. In a foreword, the Chairman of the Board, Mr. W. K. Hutchison, says that he trusts the booklet describing what has been done in this important work 'will foster in every department thought and action which will lead to still greater development of individual skill and collective efficiency.' This is a hope which will surely be fulfilled.

In 1951 the Gas Council drew up certain basic minimum recommendations concerning the facilities to be given by area boards for further education and in respect of pupilship arrangements. The S.E.G.B. accepted and put into operation substantially the whole of these recommendations. They were, however, only a part of the whole scheme of training and education which an area board may be expected to have and boards are therefore able to make whatever arrangements are best suited to their par-



Pictured, top left, instruction is given on the thermostatic control of a water heater; centre, a refresher course for gas fitters; bottom, practical demonstration of an appliance; above, a trainee chemist makes an analysis of the atmosphere inside a furnace used for testing the stability of refractory materials.

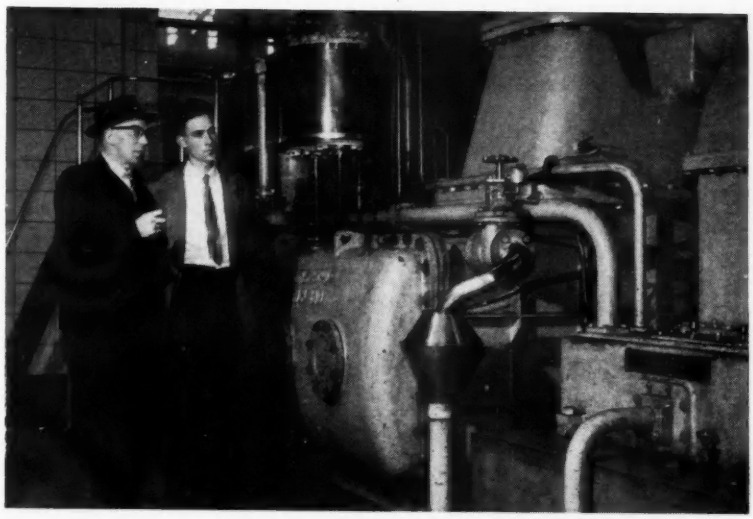
THE SOUTH EASTERN GAS BOARD

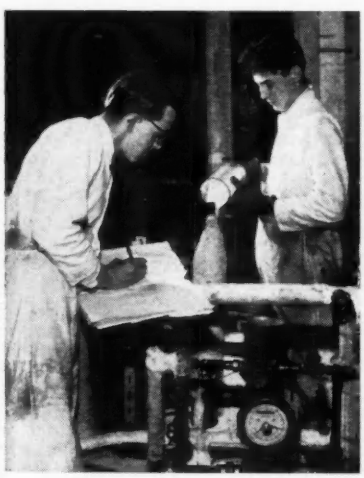
and Collective the Objectives

ticular needs and their circumstances.

The second main function of the Gas Council in this field is the co-ordination of the programmes of area boards. For this purpose the Gas Council has set up an advisory committee representative of all boards. In addition, the training and education officers of the boards meet from time to time to discuss matters of common interest.

The S.E.G.B. report explains the scope of the Board's scheme of training and education and presents the reasons, arguments and justifications forming the background of their policy in this respect. The training and education of employees of any large organisation can only be accomplished by the co-ordination of effort between that organisation, local education authorities, universities, professional institutions, and all other bodies which can contribute in any way to raising the level of attainment of the employees concerned. As the report shows, the Board's scheme is flexible and is adjusted to varying circumstances and demands. Even so, the Board feels that there may be future scope for extending and modifying what is being done.





Pictured, top right, a pupil electrical engineer receives instruction in the power house; centre, an apprentice fitter at work on a lathe; bottom, a pupil engineer using an optical pyrometer in a retort house; above, a trainee chemist works with a vacation student on problems of wet purification.

'Gas Sales Could be Doubled in Ten Years'

N.W.G.B. CHIEF AT OPENING OF METER FACTORY EXTENSION

Mr. D. P. Welman, North Western Gas Board Chairman, left, performs the opening ceremony, watched by Mr. H. P. Barker, Chairman, Parkinson Cowan, Ltd.; Mr. E. J. Spurrier, Director and Divisional Manager, Parkinson Cowan (Gas Meters), Ltd., and Mr. J. O'Brien, Works Manager.

WHEN he opened the extension to the Stretford works of Parkinson Cowan (Gas Meters), Ltd., recently, the Chairman of the North Western Gas Board, Mr. D. P. Welman, spoke of the Board's policy regarding meters. Parkinson Cowan supplied 25% of all new meters bought by the Board, he said. And the Board bought on quality and service only.

On the future, Mr. Welman said: 'If we stand still we deserve to stay rooted to the spot and die in our tracks. If, on the other hand, we have the courage of our own convictions and the brains to back it, we would put our minds to sound development on the right basis, and I would go so far as to say that in my opinon we could if we got the price right. That is on my shoulders. I am quite satisfied we could more than double the sales of gas in the North-West in something between five and ten years.'

Mr. Welman said it was the coal industry's price increases alone which had made the Board increase their price to a point which he considered high enough.

'At Partington we are putting down a gas plant on completely new methods of gasification. Three new American oil industry developments are being used. That plant is well on the way; the foundations are already being laid and we should have it ready in 18 months' time or less.

'If it can produce what we hope it will, and if we can make it alternative in its use of oil or coal of any kind—not specialised gas-making coal—I think we can produce gas at a price which can leave our competitors, including the oil industry standing.

'We are spending between £2 and £3 mill. and I think it will bring a low-price product because it will not only be almost free of sulphur, but it will also be very nearly free of carbon dioxide. So in future we will not have the uncomfortable feeling that old people living alone can damage themselves irrevocably. We will produce the ideal pipe fuel at as low a price as any other fuel industry can compete with.'

Mr. Welman, reverting to the subject of meters, said the gas industry at large had to produce smaller meters and meters which were lower in their initial price—'But that may not apply in the main to you. If we can get the price and the size down and the maintenance over a long period to an absolute minimum then I think that is your goal in meter production.'

He had been very impressed with what he had seen while viewing the shop. He had noticed great improvements and the new extension was admirable.

Mr. Welman is seen touring the new extension.

From a paper to the Seventh International Symposium at Oxford, September 2.

The Effect of Adding Auxiliary Gas on Turbulent Blow-off Stability

By F. FETTING,
OBERINGENIEUR, INSTITUT FUR TECHNISCHE CHEMIE DER TECHNISCHEN HOCHSCHULE, HANNOVER,
R. H. WILHELM,
PROFESSOR OF CHEMICAL ENGINEERING, PRINCETON UNIVERSITY,
and
A. P. H. CHOUDHURY.

As is well known, a flame in a high velocity stream of a premixed combustible gas may be anchored specially by means of a bluff-body holding device. Present work concerns blow-off limits at a 5 mm. o.d. cylindrical flame holder as the velocity of a pre-mixed propane-air stream of differing compositions is caused to increase to the condition of flame blow-off within a rectangular combustion chamber 12 by 2 by ½ in. Fig. 1 shows the position of the holder within the duct and Fig. 2 illustrates the parts of the flame as seen through Vicor glass windows. By perturbing conditions experimentally near the flame-holder it is sought to explore the blow-off process and to gain insight regarding the location of the seat of blow-off stability, relationships between the different parts of the flame structure in the stabilisation processes and possibly the part chemistry plays in the process. System disturbances were geometric and gas compositional in nature. In some experiments the normal, cylindrical holder is replaced by streamline shaped bodies which protrude into and fill the wake region to different extents. In other experiments local gas compositions in the immediate vicinity of the holder surface are modified from those existing because of normal contributions from the primary propane-air stream and from the recirculating wake gas. These modifications are made by adding, in turn, small, controlled quantities of various pure combustible, oxidiser and inert gases through small holes from within hollow-flame holders in one of three directions, downstream, upstream and at the separation positions.

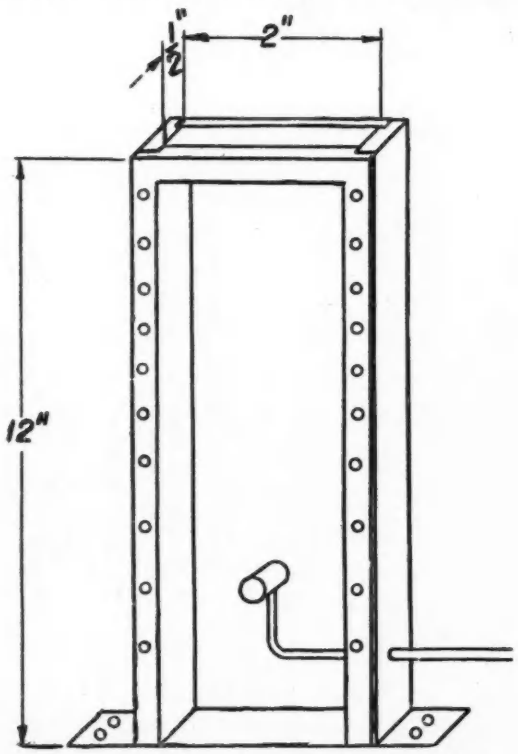


Fig. 1. Combustion chamber with flameholder in position.

The particular experiments in turbulent flame blow-off here reported are an extension of previous work on blow-off stability in laminar flames.[13] In laminar flames blow-off characteristics were found to be affected markedly in a modified Bunsen burner by the introduction of small continuous quantities of auxiliary gas into the immediate vicinity of the burner lip attachment zone. In this background study, auxiliary combustible gases were found to raise the blow-off limit substantially for lean mixtures of the main premixed gain stream; oxygen acted in a like manner for rich mixtures. Inert gases tended to depress blow-off limits. The rate of supply of auxiliary gas was insufficient to change measurably the adiabatic burning velocity as determined in the combustion wave distant from the burner lip. It was concluded that a stabilising ignition zone in a laminar flame is resident in the region near the burner lip in which streams of premixed combustible gases and convective streams of the gas surrounding the burner (air in most instances) join and mix. The resulting intermediate gas composition is characteristic only of the local zone and not of the adiabatic combustion wave farther distant. These results suggested that a similar local laminar boundary layer juncture zone be sought also in relation to blow-

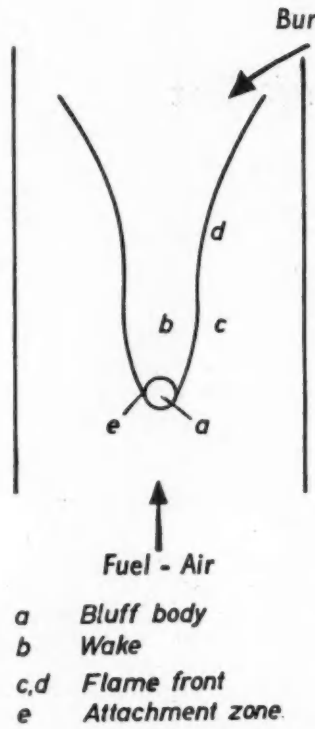


Fig. 2. Flame and flameholder in combustion chamber.

off stabilisation of turbulent flames and that the relative rôles of premix combustible gas stream and surrounding atmospheric gas of the bunsen burner may be analogous to combustible gas and re-circulating wake gas streams, respectively, in the case of turbulent flames.

Flame attachment and blow-off in high velocity premixed gas streams have become classic areas of study and the literature is extensive. Recent summaries of the literature are given by John Mayer[3] and by Childs[1]. References pertinent to present work will be given in connection with the discussion of results.

The combustion chamber (Fig. 1) is the same as that used and described by John and Summerfield[1, 3]. The chamber was provided with a gas mixing section, calming screens and a converging nozzle designed to give a flat velocity profile at the combustion chamber entrance. The flame-holder was positioned as shown in Fig. 1. An auxiliary hydrogen pilot flame was introduced through a side port to ignite a flame at the holder position, the port being closed after this operation.

The majority of experiments were conducted with hollow, stainless steel cylindrical flame-holders, 5 mm. in diameter. Three variants of the holders were prepared with rows of small holes drilled through the cylinder surface parallel to the axis to permit flow of small streams of auxiliary gas from within the holder into various regions surrounding the holder. Radius angle positioning of holes in the three holders is indicated in Fig. 3 for upstream, downstream and sidestream injection. In the last case, rows of holes are provided on both sides of the holder. The figure shows also relative positions of the free layer separation point and the location of the end of the luminous flame tip. The size and numbers of holes are as follows: Upstream, six holes, 1.07 mm. in diameter; sidestream, six holes in each row, 0.275 mm. in diameter; downstream, three holes, 0.8 mm. in diameter. Holes were uniformly spaced in the axial direction. However, because of the presence of a 1.68 mm. diameter stainless-steel lead-in tube at the upstream location, injection holes were drilled laterally on either side of the tube.

Certain experiments were performed with flameholders having approximately streamline shapes. Relative sizes of the three elongated holders are shown in Fig. 4; all were 5 mm. in projected diameter, this dimension being common between the cylindrical holders and the present set. Holder I was provided with sidestream holes for auxiliary gas introduction with radius angle placement the same as in the corresponding cylindrical holder. Some blow-off experiments were performed prior to drilling these parts to determine whether the surface roughness caused by the presence of the holes might affect blow-off properties (it did not). Holders II and III were fitted with a means for internal water cooling but none for auxiliary gas introduction.

The primary, pre-mixed gas stream consisted of propane-air mixtures of various compositions. Propane was of commercial purity, about 95% propane and 5% other hydrocarbons. Propane flow was measured with a calibrated standard orifice and air flow, with a Koerting rotameter. Normal corrections for pressure and temperature were performed in determining flow rates of the individual gas streams, and through these, the mixture composition.

Small streams of auxiliary gas were introduced into the flame-holder directly from gas cylinders after being measured with a calibrated capillary flow meter or a small rotameter. Purities and sources of the auxiliary gases were as follows:

Gas.	Purity.	Source
N_2	99.9%	American Oxygen Co., water pumped
O_2	99.5%	" " " electrolytic
He	99.9%	" " "
H_2	99.8%	" " " electrolytic
CH_4	99.0%	The Matheson Co., Inc., c.p.
C_2H_6	99.6%	" " " instrument grade
C_4H_{10}	99.6%	" " " " "
CO	99.6%	" " " " "

Schlieren photographs as well as normal pictures of the region of the flameholder were taken. The Schlieren assembly consisted of a tungsten arc light source, a small aperture, a lens, two parabolic mirrors, a razor knife edge and a speed graphic camera with ground glass viewer. Analyses of the CO content of the wake

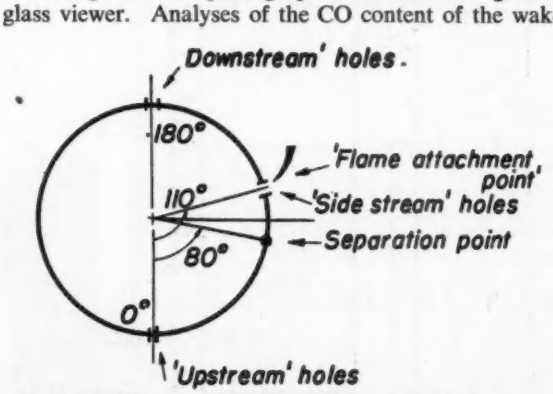


Fig. 3. Radial angle positions of rows of auxiliary injection gas ports in three cylindrical flameholders, providing for upstream, downstream and sidestream gas introduction.

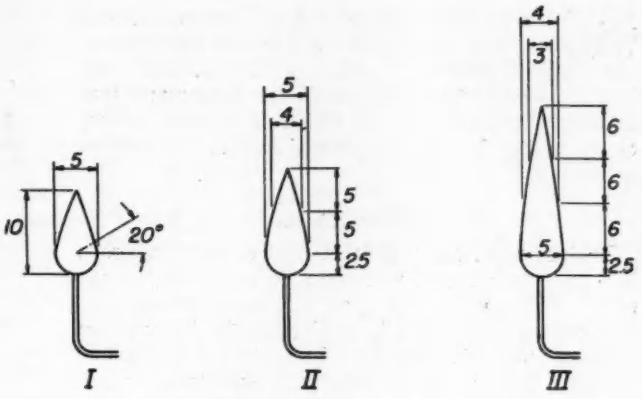


Fig. 4. Flameholders with approximately streamlined shapes. Holder I in two variants had smooth surfaces in one and drilled auxiliary gas port holes in the other. Holders II and III were provided with internal water cooling.

were performed quantitatively with a Perkin-Elmer infra-red analyser, using the rotational banks of CO in the vicinity of 4.67μ. Gas samples were taken in evacuated bulbs and were dried with calcium chloride.

An initial step toward determining a blow-off velocity was to establish an equilibrium propane-air flame at a pre-determined total gas flow rate and with a composition close to the stoichiometric. A hydrogen pilot light initiated the combustion at the flame-holder. After one or two minutes of operation, to achieve thermal equilibrium at the flame-holder, the propane flow rate was increased or decreased, until blow-off occurred, air rate remaining constant. Through this procedure, gas composition and total gas flow rate are varied simultaneously. Use of the opposite procedure, namely, varying air flow rate at constant propane rate gave equivalent blow-off results. When auxiliary gases were introduced, constancy in flow rate of these gases was maintained by successive adjustments to allow for pressure changes near the holder as main gas stream flow changes were made.

Clearly Defined

Blow-off limits ordinarily were abrupt and clearly defined. Some uncertainty in definition of blow-off limits occurred, however, in the case of lean propane-air mixtures when auxiliary fuel was introduced locally, and also for rich propane-air mixtures when auxiliary oxygen was introduced. In either condition for low blow-off velocities, small residual flames tended to remain in the wake region after the main flame lobes had become extinguished. In all cases, the gas velocity required for extinction of the main flame was taken as the blow-off velocity. On various blow-off velocity-gas composition curves the approximate velocity beyond which the residual flame is not stable is marked R.F.O. (residual flame out).

Standard experiments of blow-off velocity *versus* propane composition, expressed as fraction of stoichiometric, were determined at intervals over the period of one year, as shown in a composite curve in Fig. 5. The random variations of data points about the mean curve represent contributions due to the use of a succession of propane cylinders and also due to normal measurement errors in gas flow and composition. In preparing the standard curve it was necessary to close the inlet tube, intended ultimately for supplying auxiliary gases. Particularly in the case of the flame-holder with downstream injection ports, the higher-than-ambient pressure in the wake caused a backflow of wake gases into the holder, with subsequent overheating, unless the entry tube was closed.

Experimental results fall into two categories: Geometric, relating to the location of the flame anchoring and stabilisation region, and chemical, relating to effect of local gas compositional changes in that region on the gross stability limit as measured by flame blow-off.

Geometric results. The region near the free-layer separation point and the wake region immediately downstream of this point was studied photographically by means of Schlieren and direct image photography. Geometric considerations also appear in blow-off measurements as these are affected by the shape of the holder, progressing from the cylindrical to shapes I, II and III, as illustrated in Fig. 4.

Layer Visible

For ready photography a solid cylindrical holder 12.5 mm. in diameter was used, rather than the normal 5 mm. size. By sighting on the end of the holder the thermal free layer is rendered visible in a Schlieren photograph while a steady flame is anchored to the holder. The density gradient to which Schlieren photography is sensitive arises through the heating of premixed gas in a boundary layer contact with the flame-heated holder prior to separation. The original paper includes Schlieren photographs showing such a layer at a Reynolds number of 4,000. The thermal free layer was found to persist as much as one minute after flame extinction because sensible heat in the holder continued to be transferred to the upstream boundary layer. In Schlieren photographs taken 10 seconds after flame extinction the location of the thermal free boundary layer is seen to be substantially the same, whether or not the flame is present. The approximate separation point of 80° is consistent with past studies[11]. In Schlieren and direct photographs of a flame for a Reynolds number of 16,000, the luminous flame is observed to lie directly adjacent to the wake side of the thermal boundary layer and to lean inward, away from the thermal layer in the immediate vicinity of the holder. A final photograph shows the development of a density-gradient free layer through the introduction of butane into the wake of a cylindrical holder at

N_{Re} of 4,000 in the absence of flame, the main stream being air. The circulation path in the wake carries the butane from the point of introduction high in the wake (the tube tip shows in the photograph) well into the fillet formed by the free layer with the surface of the holder, but not completely back to the point of separation.

Similar Effects

The use of streamlined flame-holders which protrude into the wake region was intended to investigate the effect of blow-off limits as the re-circulating gas flow pattern in the wake is modified by the introduction of these geometric obstacles. It was found that holder I with a length : diameter ratio of 2 and straight sides, gave a closely similar blow-off curve to that for the standard cylinder of equal diameter. These results are shown in Fig. 7. It was found that the addition of auxiliary gases from side ports also gave quantitatively similar effects between these two holders. Thus holder I and cylindrical holders are concluded to have similar flame stabilisation properties; holder II, with a length : diameter ratio of 2.5 and rounded sides, on the other hand, was shown to decrease flame stability substantially, as shown in Fig. 7. These results are for an uncooled device. Furthermore the flame did not appear to maintain a steady base, but it oscillated on the surface of the final, *i.e.*, trailing, third of the holder length, leading to the appearance of a brushy flame. When flame holder II was water-cooled, it was not possible to stabilise a flame on it, as was also the case, under all circumstances, for holder III, which had length : diameter ratio of 4.05 and rounded sides.

Effect of auxiliary gas addition in stability limits. In a further eight curves given in the paper the effects on

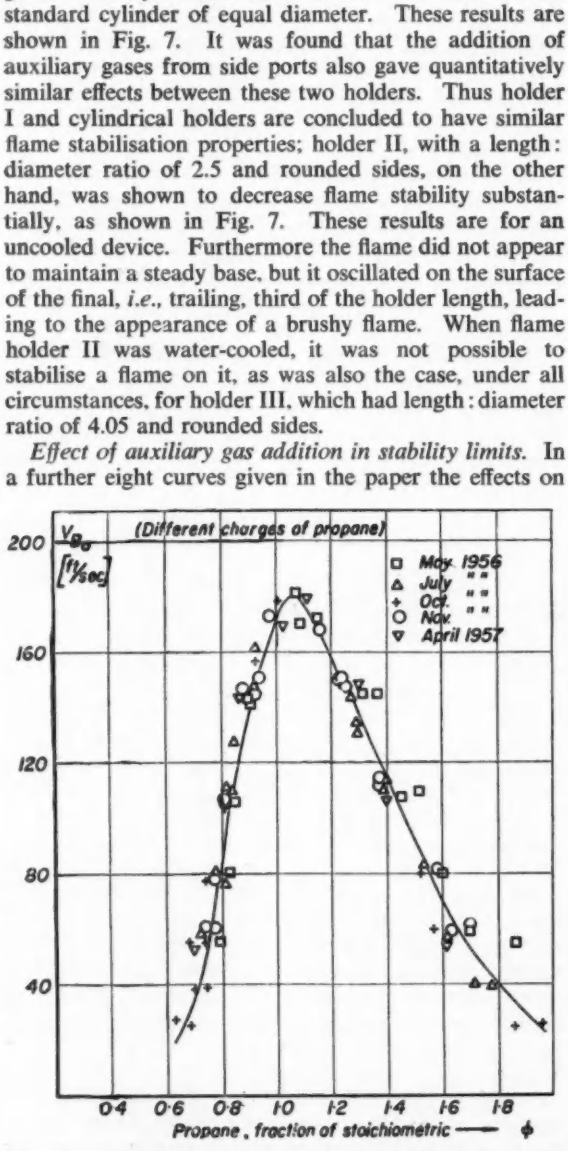


Fig. 5. Standard propane-air blow-off curve, blow-off velocity versus propane composition expressed as fraction of stoichiometric. Data were taken at intervals over a period of one year and with different supplies of propane.

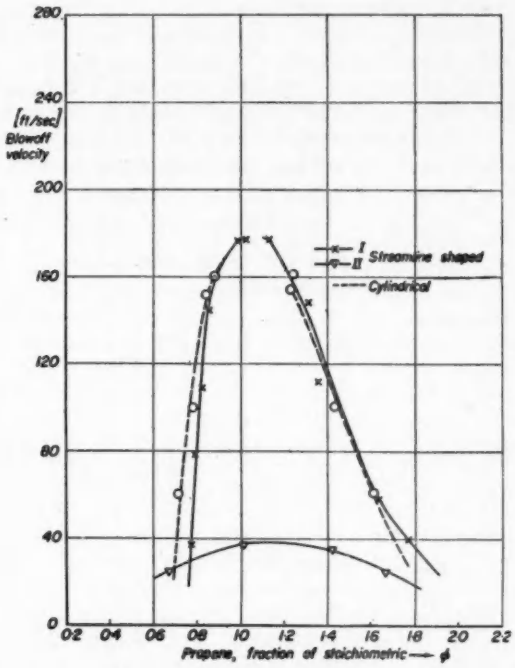


Fig. 6. Comparison of blow-off limits of streamlined flameholders compared to standard cylindrical holders. Holder geometrics are recorded in Fig. 4.

the characteristic blow-off curve are shown as the result of introducing small flows at different radial holder positions of inert, of oxidising and of combustible gases. The reference blow-off curve in each figure presents a base for judgment, it having been determined in the absence of auxiliary gas injection and with the same propane supply as the remainder of the data in that plot. Curves representing different constant auxiliary gas rates were secured by interpolation of data relating gas injection rate, equivalence ratio and blow-off velocities. During measurements, the rates of auxiliary gas were between 1.5 and 6.5 cu. cm. per second for all gases except H_2 and He, for which the rates were between 2 and 18 cu. cm. per second.

Velocity Decrease

It was observed that the addition of inert gases, N_2 and He decreases the blow-off velocity only slightly with an approximately uniform decrease at all equivalence ratios. Aside from dilution, inert gases seem to play a small rôle in the attachment-stabilisation process. The addition, on the other hand, of O_2, H_2, CH_4, C_3H_8, C_4H_{10} and CO had certain similar effects which occur to varying extents. The entire blow-off curve is shifted with a change in the maximum toward a richer main gas composition in the case of O_2 addition, and toward leaner compositions in the case of all combustible gas additions. For all auxiliary gases the maximum of the blow-off curves is increased to larger values by auxiliary gas addition. In all cases, also, the addition of auxiliary gases in larger rates led to larger effects on blow-off limits. The positive effects on blow-off of introducing auxiliary gases in upstream or sidestream positions were closely similar in magnitude. However, the addition of auxiliary gas from the holder in a downstream direc-

tion, into the wake, led to greater increases in blow-off limits than did additions either in the upstream or side-stream directions.

Very substantial increases in blow-off limits were achieved on the addition of auxiliary oxygen, at 2.5 and 5.0 cu. cm. per second rates, especially into the wake region. It was noted that the lean lobe of the normal blow-off curve is but little affected by oxygen addition whereas the rich lobe blow-off limits are increased for all modes of addition. The composition of CO in the wake during normal combustion of rich propane-air mixtures was measured by means of infra-red analysis and was recorded on a water-free basis. Thus surplus fuel is available for combustion in the wake by means of the auxiliary oxygen. At lower free stream velocities and in the case of oxygen introduction into the wake small flame cups could be observed within the wake attached at the three points of oxygen introduction. These small flames were present especially for stoichiometric and richer free stream compositions, but they persisted, but more weakly, for a small equivalence interval into the lean side of the gross propane-air combustion. High main stream velocities caused the separated cups to join in forming a single flame front within the wake. It seems evident that one contribution of auxiliary oxygen addition is to increase the temperature of the wake by means of the auxiliary flame within the wake, thereby affecting ultimately the blow-off limits of the main flame.

In regard to the introduction of auxiliary hydrogen on blow-off, it is observed that this gas is particularly effective in increasing the blow-off limit and that major increase occurs in lean propane-air main stream mixtures. In connection with downstream addition experiments, it should be recalled that lean flames commonly contain oxygen in the wake. The addition of hydrogen (or other combustible) to the wake thus serves to increase the value of the wake gas as a low grade pre-mixed fuel which may release heat energy in an ignition stabilisation zone of the primary flame.

The shifted blow-off curves resulting from addition of methane, propane and butane were noted. All followed the pattern of a shift of maximum to lean values of the main stream propane composition as well as an increase in the maximum. Equal volume rates of auxiliary gas additions were compared. The smallest effect on extending blow-off velocity is that of methane, next is butane and highest effect is due to propane. This order corresponds to the order of adiabatic flame temperatures for these auxiliary gases when burned individually in air.

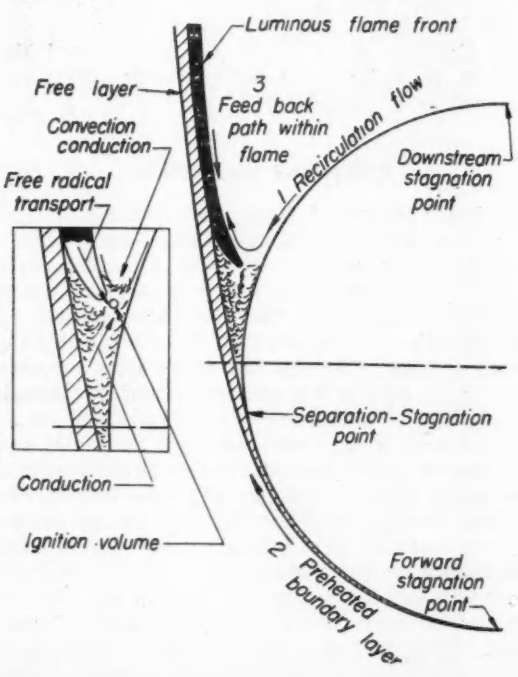


Fig. 7. Diagrammatic representation of the flame attachment zone showing various flow and heat and mass transport paths.

Positive Changes

The introduction of CO into the holder vicinity led to positive changes, characteristic of active chemical species, but the extent of change was small.

Although the number depends upon the dimensions of the burner duct and it is not basic, it is of interest to estimate the amount of auxiliary gas employed compared to the propane flow in the combustion chamber. Considering propane as the auxiliary gas as well as the free-stream gas, at maximum blow-off conditions of 280 ft. per second and $\phi = .8$, where ϕ is the fraction stiochiometric quantity of propane, a propane injection rate of 2.5 cu. cm. per second corresponds to 1/1,000 of the main stream propane flow rate.

Basis for Discussion

A representation of the visual flame location near the holder in Fig. 7, together with Fig. 2 and the photographs referred to above, provide a basis for discussing present results. Two streams of gas flow around the holder and converge in the region of flame attachment. Of these, one is the pre-mixed gas, which, starting at the forward stagnation point forms a boundary layer that separates from the cylinder at about 80° to form a free layer. The steep velocity gradients in such a layer for the same Reynolds number range (N_{Re} between 1,000 and 10,000) have been detailed by Schiller and Linke[11]. The other stream is the well-known re-circulation eddy system in the wake which causes a local flow near the surface from the downstream stagnation point back toward the separation point, finally changing direction, tending to become parallel to the free layer. The flame was observed to be attached closely to the inner, wake side of the free boundary layer. However, the flame attachment tip was noted to lean in toward the holder and away from the free layer, an elongated triangle being formed between the flame, the free layer and the holder surface. As has been photographed by Prandtl[9] and others, the region of discontinuity for a cylinder lying between the stagnation-separation point and the region of gross re-circulation pattern is populated by small eddies which have shed from the free layer directly after separation. Transport within this triangle region of eddying motion presumably is substantially larger than for molecular processes, thereby providing a rapid diffusive means for transporting heat and

reactants from the free layer of pre-mixed gases to the flame tip and ignition region. The location of the flame is suggested to be at an interface between gross flow patterns of hot re-circulating wake gas on the one side and a region of fine grained eddy patterns on the other. The flame stabilisation region thus is linked spacially to the stagnation-separation point on the holder surface through the zone discontinuity. In effect, this model represents the flame as lying along a highly porous septum through which reactants diffuse and along which a hot gas flows.

Stabilisation of the flame is considered to reside in a small volume element that lies on an extension of the flame in the direction of the holder surface, well beyond the visible tip. The properties of the fluid in the elementary volume are fixed in space in relation to the holder position by the hydrodynamic situation described above. The volume element is supplied with reactants and heat through various flow and transport processes. A heat production rate by reaction is maintained continuously such that a finite positive temperature gradient will exist at the element, the size of which increases continuously with position along a trace between the ignition volume element and the luminous flame tip. This is suggested to be ignition in a flow system.

Three Paths

It will be of interest now to trace various transport paths in Fig. 7 by which the ignition zone and the adjacent flame tip are likely to be supplied with reactants and heat. There are suggested to be three such paths, the re-circulation flow of wake gases, the boundary layer formed by the approaching pre-mixed gases at the holder surface together with its extension as a free layer and finally a feedback path from the flame proper to the zone of ignition.

Part of the burnt gases from the flame circulate in the wake and in so doing provide heat by conduction-convection to the ignition zone from the circulating stream. According to Zukoski and Marble[15] the measured temperature in the wake is quite uniform throughout the wake and it does not change appreciably as the blow-off limit is approached. At the same time the wake stream tends to dilute the composition of the reactant gases in the critical ignition volume with inert combustion gases, the resultant steady-state composition at that location being different than that of the pre-mixed main stream gas to which blow-off velocity commonly is related empirically. As dictated by the detailed processes of mixing and burning in the turbulent flame, at a distance from the holder, there may be small quantities of excess oxygen or combustible in the wake when main stream compositions are lean or rich, respectively.

Such reactant components in the wake contribute to reaction and heat release rates in the critical ignition volume. Also, the hot circulating vortex, in flowing over the exposed surface of the holder transfers heat to it. This heat is conducted by the holder to the upstream surface where it serves to heat a layer of pre-mixed gas that is in process of forming a boundary layer as it flows over an 80° arc from the forward stagnation point to the point of separation. A thermal boundary layer is formed as a result, which, separating with the velocity boundary layer, forms an associated combination of free heat and velocity layers. A Schlieren photograph of the density gradient in the thermal free layer gave evidence that the position of the layer, starting at the separation point, was not different in the presence or absence of the flame.

A slight thickening of the Schlieren image during combustion was noted, however, in the vicinity of the luminous flame tip. The broadened density or temperature gradient is suggested to be the result of a local thermally induced enhancement of mixing and heat transport rate in the triangular, fine vortex mixing zone. As discussed above, this transition zone is presumed to be a high conductivity region by means of which combustible reactants at the inner temperature of the boundary layer are curled off that layer and transferred to the part of the flame axis lying between the ignition point and the luminous flame tip.

In considering the third path, the feedback flux of energy along the flame axis in the direction toward the holder, progressing from the luminous zone, through the flame tip to the ignition volume element, a number of possible energy carriers may be contemplated, such as radiant energy electrons, protons, free radicals and atoms and charged radicals. Electrons and protons are present in extremely small concentrations, radicals have relatively low mobility and radical-radical collisions as chain breakers tend to limit chain lengths. These entities therefore are not considered of likely importance in the process. The absorption of radiant energy is a slight possibility, but strongest immediate experimental evidence concerns a likely re-combination of hydrogen atoms which have high mobility and which, in comparison with other radicals, can travel relatively far before a third body collision permits release of energy by re-combination. H − H re-combination releases 1,000 Kcal, per mole. Hydrogen atoms also initiate combustion chains in pre-mix gas at non-flame temperatures, releasing heat.

Component Mechanisms

Hydrogen atom diffusion and re-combination has been considered one of the component mechanisms in determining the velocity with which a flame progresses into unburned gas; it is here suggested also as a mechanism by which heat is introduced into the ignition volume element and so effecting blow-off stability. Support for this view comes from a study of Lapidus, Rosen and Wilhelm[6] who found exceptionally that the rate of flame ignition and travel from one end to another of a slot burner changed measurably and reproducibly as the catalytic nature of the burner lip was varied. On the assumption that the different rates of flame propagation were due to a change in free radical concentration at the flame front because of re-combination at the surface a theoretical model was proposed which led to quantitative values of surface re-combination coefficients relative to platinum surfaces.

For dry surfaces the relative coefficients were these: Platinum, 1, brass, 10; magnesium oxide, .0001. When humidified, all surfaces gave recombination coefficients smaller than .0001. Thus, if radicals can reach the surface of a flame holder, as is indicated above, then such

radicals will certainly reach the ignition volume element which lies between the surface and the luminous flame, *i.e.*, the source.

The simultaneous diffusion of radicals and heat from the flame attachment tip to the ignition zone may be regarded as contributory to blow-off stability as the same phenomena in a direction lateral to the surface commonly is considered to be contributory to flame propagation.

The various experimental results now are discussed in terms of the model of flame attachment presented above. Broadly speaking, blow-off is considered to occur when the equations of change for the ignition volume element representing all physical and chemical processes of reaction, diffusion and flow become unstable to perturbations in temperature, flow rate or composition as the mean velocity is increased.

Stabilisation appears to be associated in its positioning with a stagnation point resulting from the counterflow of the combustible gas and a second, stabilising gas stream. The latter commonly is induced by the flame itself, as in the vortex motions of bluff body stabilisers. In the Bunsen burner also a stabilising flow of air, induced by the rising combustion gases, meets the combustible gas at the burner lip at a stagnation point where stabilisation takes place. Schaffer and Cambel[12] showed that stabilisation can occur using an opposing, stabilising jet. At a cylindrical holder such as was studied here, the actual stabilisation point is some distance removed from the stagnation point in question, which is the separation point. When streamlined holders, such as I, II, III are used the recirculation flow is slowed with increasing length of holder. The size of the transition triangle increases and the flame tends to stabilise farther away from the separation point, calling for a diffusion of reactants over longer distances from the free layer to the stabilisation point. Eventually, a completely unstable situation ensues when heat and mass balances can no longer be maintained. This occurred between the geometric configurations represented by holders II and III.

Shown Experimentally

That the path for heat supply from the wake vortex stream to the ignition volume is important is shown experimentally, first by the fact that holder body II when cooled with water did not stabilise a flame, whereas it did so, although to low degree, when no coolant was provided and the holder became heated. A small difference in the heat balance at the ignition volume element spelled the difference in behaviour. A second item of evidence is given by the effect of auxiliary oxygen in greatly increasing stability limits. Since the oxygen burned with carbon monoxide in the wake in a small. auxiliary flame, the temperature of the wake was raised directly thereby favouring the heat balance at the ignition point.

The addition of chemically active gases shifted the position of the blow-off curve on the propane-air main stream gas composition. It is suggested that the auxiliary gases simply served to modify the composition for reaction at the ignition point which normally consists of some proportion of main stream and wake gases. In principle, blow-off velocities should be related to the ignition volume element composition, were it accessible, rather than main stream composition. The important compositional contribution that the stabilising gas has to the blow-off process is illustrated also[7, 13] in laminar combustion blow-off when conducted in a surrounding (stabilising gas) atmosphere of air, compared to an inert atmosphere.

The differences in blow-off curves when auxiliary gases were introduced into the wake, compared to introduction through upstream or sidestream ports are consistent with the model portrayed above. Visual observation and photographs showed the flame tip in the vicinity of the holder surface to lean away from the free layer and toward the recirculation zone. Thus gases introduced into the wake are within a short diffusion-flow path of the stabilisation volume element. Those gases, on the other hand, that are introduced exterior to the wake must traverse by diffusive means through the triangular region of discontinuity. The latter path evidently has the higher transport resistance.

Differing Values

That the nature of the chemical species of auxiliary gas may be important in the blow-out process is suggested by the differing values of blow-off maxima achieved with different gases. The large effect of hydrogen gas, with its high burning velocity and heat of combustion is evident in this regard and the relative ordering of blow-off with the hydrocarbon additive, methane, butane and propane, in accordance with flame temperatures is indicative of ordered contributions to the heat balance in the critical region.

In the present experimental paper it is not proposed to review theories of blow-off, which has been done recently[1, 3], but only to comment briefly on these in relation to the discussion above. Because of the manifest difficulty of including all pertinent chemical kinetic, heat and mass transport and fluid mechanical terms in a mathematical analysis, selections of terms have been made by various authors, for example, by placing emphasis on fluid mechanical aspects, on heat transfer aspects or on chemical rate aspects or on certain combinations as being critical in determining stabilisation and blow-off criteria. In one mode of approach, chemical kinetics is embodied in flame velocity, in another, fluid mechanics are simplified by assuming complete stirring. Some of the problems encountered in determining whether a system may or may not be stable in relation to the selection or rejection of terms in the equations of change are illustrated in recent papers on stability limits of a laminar combustion wave[14, 10].

A recent direct approach in stabilisation analysis is that of Kovitz and Cheng[4, 5] in an adjacent paper. This paper is a generalisation of that by Marble and Adamson[8]. A simple geometry is adopted, that of a cold combustible gas joining with a hot inert gas beyond a separating plane. In a boundary layer approximation for the full set of equations of change, simple chemistry as well as mass and heat fluxes are introduced in detail. There is no *a priori* selection of classes of terms to be included in the formulation. Solution leads to the definition of a characteristic length x, a distance beyond the point of stream confluence, at which a temperature bulge in the lateral profile begins to appear. The bulge results from the increasing importance of reaction heat release compared to heat removal processes.

A paper presented to the Seventh International Symposium on Combustion at Oxford on September 3.

The Vertical Tube Reactor—A Tool for Study of Flame Processes

By K. G. WILLIAMS, J. E. JOHNSON and H. W. CARHART.

STUDIES of flame development in a heated vertical tube have shown it is possible to separate and stabilise in a single apparatus the various stages which lead to normal flames in the autoignition process. The first clearly marked phase in this process is the development of a low intensity combustion wave known as a cool flame. The cool flame, which gives off some heat and a pale bluish light, spectrally characteristic of activated formaldehyde, has been examined by many investigators, a few of whom are cited[1, 2, 3, 4].

The cool flame is self-inhibiting and never releases the total available chemical enthalpy of the system so the final products contain partially oxygenated materials such as aldehydes and peroxide. While the mechanism of the inhibition is not yet unambiguously understood, it seems to be related to a negative temperature coefficient of reaction which operates to reduce the extent of reaction in the cool flame as the temperature is raised beyond a critical zone[5, 6]. This effect is not always easy to observe because reactions subsequent to the cool flame are not similarly inhibited. Nevertheless it often serves to confine the cool flame to a relatively low percentage of the available reactants so that oxidising gas, unaltered fuel, and cool flame products are available for further reaction.

The maximum temperature attained by the cool flame is seldom more than 100-150°C. above its initiation temperature (250-400°C.) and is not sufficient to initiate directly a normal combustion wave. The necessary additional temperature increase arises from a second chain-branching process, separated in time from the cool flame. This delay, like the cool flame induction period, seems to arise from the necessity of generating a sufficient concentration of chain initiators.

The development of the second stage culminates in a blue flame of sufficiently great luminosity so it can readily be seen in subdued light. Emission from this blue second-stage flame, under fuel rich conditions where subsequent thermal reactions do not complicate the spectrum, is nearly identical to that of the cool flame[7, 8].

The temperature rise in the blue flame depends primarily on the availability and proportions of reactants. When conditions are favourable, normal combustion is initiated. The fully developed combustion wave is characterised spectrally by emission from fragmentary particles such as OH, C_2 and H_2O.

Under many conditions, where autoignition occurs, the controlling induction period is that of the cool flame. Once this has been initiated the subsequent transitions occur with such rapidity and inhomogeneity that the stepwise nature of the process is obscured. To study details of the discrete stages, they may be separated in either time or space. While each approach is subject to inherent disadvantages, both have been used with success.

This paper deals with an experimental technique based on a vertical reactor for separating the stages leading to normal combustion so that each can be examined in either the presence or absence of the next succeeding stage. The vertical reactor was designed originally to determine the temperature at which the autoignition process was superseded by normal combustion. There are indications from studies of Levedahl[11] and from Johnson, Crellin and Carhart[12] that this transition occurs at a temperature of 550-600°C., regardless of the cool flame susceptibility of the fuel.

Because of the extremely rapid transition from second stage to normal combustion in static systems, a flow system in which the oxygen concentration could be raised gradually to the critical level was believed to offer the best chance of success. Flat flame burners operated on this principle provide a clean distinction between the cool and second-stage flames[13, 14], but it was believed that wider separation could be achieved in a heated tube. Successful separations have been reported in horizontal heated tubes[7, 15], but temperature variations across the vertical diameter of the tube lead to oddly shaped flames having only bilateral symmetry. Since vertical mounting of the tube would provide a flame having axial symmetry, this was tried.

The separations obtained with the vertical reactor were satisfactory and gradual increase of the oxygen

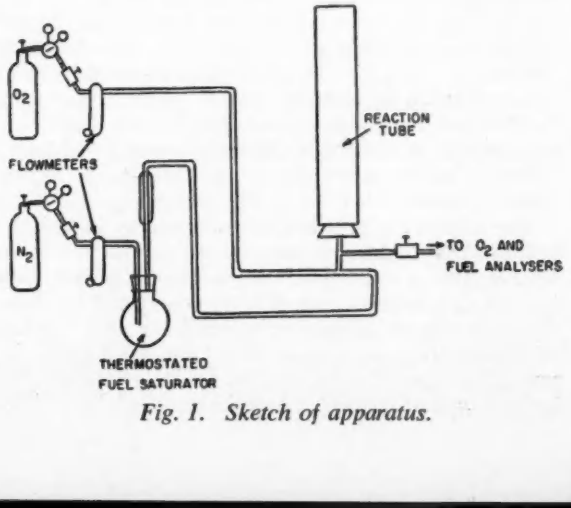


Fig. 1. Sketch of apparatus.

concentration was found to provide an excellent precession of flame stages. The method is reported below.

The initial apparatus (Fig. 1) consisted of a vertically mounted Pyrex glass tube, 42 mm. i.d. and 20 in. long. The tube was heated electrically by means of a transparent conductive coating of tin oxide fused on to the outer surface. The bottom of the tube was closed with a rubber stopper supporting a bed of glass beads ($\frac{1}{8}$ in. diameter) 2 in. in depth to disperse the gas entering through an axial hole in the stopper. A loose plug of glass wool prevented random air currents from disturbing flow at the top of the tube and the tube was shielded from draughts by a glass jacket. Ancillary equipment was limited to the pressure reducing and throttling valves and flow meters necessary to meter separate streams of oxygen and nitrogen into a mixing tee at the bottom of the reactor, a temperature controlled fuel bubbler in which the nitrogen stream was saturated with fuel vapour, a para-magnetic oxygen analyser and an infra-red absorption meter to monitor the reactant concentrations.

The tube was heated to the desired temperature while the fuel bubbler temperature and nitrogen valves were adjusted to give the desired flow conditions. Then, while observing the tube in total darkness (15-20 minutes were usually allowed for dark adaptation of the observer's eyes), the oxygen flow was started and gradually increased.

The first visible reaction appeared near the top of the tube as a diffuse cloud of luminosity several inches in length. As the oxygen flow was increased this moved downwards in the tube and coalesced into a clearly defined cool flame. Additional oxygen caused a slight additional movement downwards and decreased the apparent thickness of the luminous zone. A second diffuse cloud of luminosity then appeared near the top of the tube (usually also along the walls) and as the oxygen flow continued to increase, coalesced into the second-stage flame which was clearly separated from the cool flame and was considerably brighter. Additional oxygen decreased the separation of the two stages and led very gradually to a column of orange luminosity in the wake of the second-stage flame. This increased in intensity and spread out to form a sooty candle-like flame bright enough so that the cool flame could no longer be seen. Additional oxygen caused this flame to break up into a hollow cylinder made up of several cusps which rotated slowly in the tube.

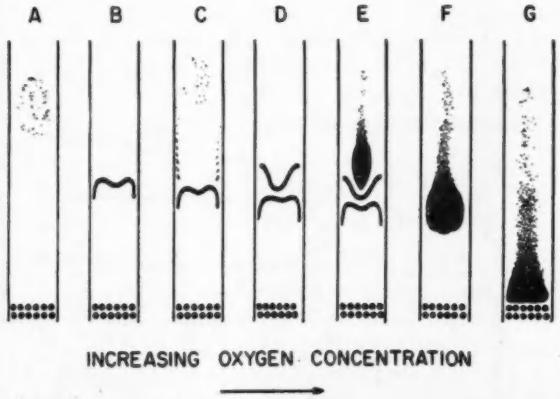


Fig. 2. Sketch of observed flame stages. (A) Diffuse pre-cool flame luminosity; (B) coalesced cool flame; (C) cool flame plus wall luminescence and diffuse luminosity; (D) cool flame and blue second-stage flame; (E) developing orange flame; (F) cylindrical, cusped flame; (G) thermally self-sustaining flame stabilised at bottom of tube.

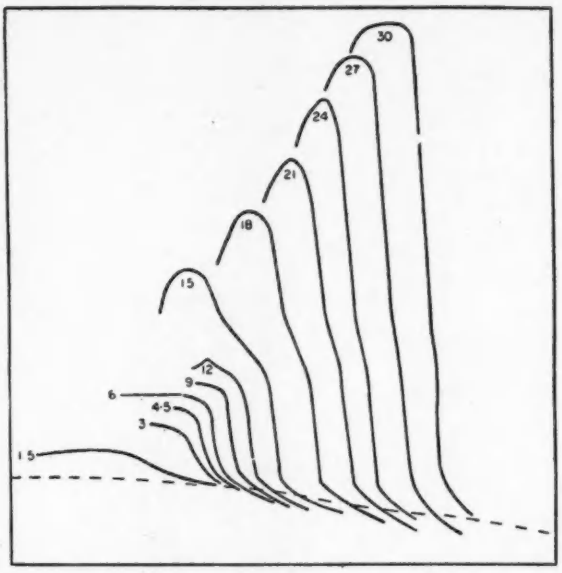


Fig. 3. Temperature profiles along axis of reactor at succession oxygen levels traced from potentiometer record. Thermocouple position is plotted horizontally and millivolt output vertically. Tube diameter 62 mm. Total distance represents about 40 cm. Direction of gas flow is from right to left. Figures on curves denote present oxygen. Initial tube temperature 350°C. with no oxygen flow (dashed line). Basic flow—4 litres per minute. Fuel—n-hexane (15% of basic flow).

Up to this point the flame structure was completely stable and could be smoothly retrograded by decreasing the oxygen flow. Beyond this point the cusps elongated and probed erratically towards the bottom of the tube, eventually pulling the whole flame structure down to the beads. Additional oxygen increased the intensity and whiteness of this stabilised flame. Still more oxygen caused the flame to flash back abruptly through the bed of glass beads and to burn vigorously in the $\frac{1}{8}$ in. diameter passages of the mixing tee. Sketches of these steps are shown in Figure 2. The stability of the cool flame was such that colour photographs taken with a ten-minute exposure showed no appreciable movement.

To determine the position of the various flame stages a thermocouple was mounted so that it could be moved along the axis of the tube. The couple was made of platinum and platinum-rhodium wire about .003 in. diameter covered with a thin sheath of glass to minimise catalytic effects. It was supported on a yoke which maintained its axial positioning and the lead wires were brought out along the walls to minimise their influence on the flame. The output was fed into a potentiometric function plotter which recorded thermocouple output against its position. Replicate runs made with the couple moving upward through the flame at rates not exceeding 5 c.m. per minute gave results agreeing with the reading error of the potentiometer and

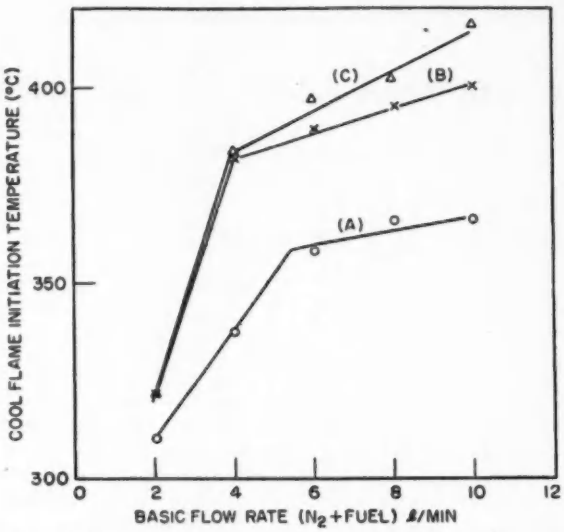


Fig. 4. Effect of basic flow rate on initiation temperature of cool flame. Plots A, B and C were made at tube temperatures of 300°, 350° and 400°C. respectively. Oxygen 27%. Fuel n-hexane (15% of basic flow). Tube diameter 62 mm.

could be reproduced by moving the couple downwards but at a greatly reduced rate. Corrections were not applied to the reported temperatures.

To give a comprehensive picture of the developing flame structure, temperature profiles at several oxygen levels were plotted on the same sheet. A tracing of such a record is shown in Fig. 3. The luminous zones correspond to the zones of maximum rate of temperature rise with the exception of the orange luminosity which arises in the wake of the second-stage flame. This orange luminosity leaves no specific indication of its existence on the thermocouple trace. It may be seen in Fig. 3 that the temperatures in both the cool and second-stage flames increase linearly with distance. In the space between these stages the temperature also increases linearly. This is most easily seen at the lower oxygen concentrations. When the curves in Fig. 3 are expanded and corrected for the base-line temperature profile, a zone of linear temperature rise becomes apparent just ahead of the cool flame.

Following the development of the temperature plotting system, studies were made of several operating parameters. The observations were limited to oxygen concentrations which permitted good control of the flame (Phases *A* through *E* in Fig. 2); these are discussed individually below.

For a given tube, the basic flow (N_2+fuel) could be varied satisfactorily by a ratio of at least 5:1, corresponding to linear flow rates of 2.1 to 10.5 cm. per second (calculated for 350°C.). The upper limit was imposed by the onset of turbulence which disturbed the flame structure. At low rates the flame structure became compressed and approached the glass beads at the bottom too closely to permit meaningful temperature measurements with the thermocouple used. Changes in flow rate had a marked effect on the shape of the flame. At low flows both the cool and second-stage flames were quite flat and approximated the configuration of published photographs of two-stage flames obtained on flat flame burners[13, 14]. At higher flows, the cool flame assumed a dimpled button shape which elongated into a truncated re-entrant cone at the highest flows. This folded structure seemed to arise from a disturbance of the parabolic Poisselle distribution of velocity characteristic of isothermal cylindrical flow as a result of convective rise as heat is transferred inward from the walls. This folding process contributes to the stability of the flame position by providing a means of adjusting the flame area to the flow rate so that the characteristic propagation velocity of the mixture can be maintained.

The second-stage flame, flat at very low flows, develops into an increasingly steep cone as the flow is increased. This shape arises from the necessity of maintaining a flame area in equilibrium with the flow rate and burning velocity and at the same time compensating for energy losses to the walls. The reality of these losses were demonstrated by displacing the thermocouple from the axis to a position near the wall. Vertical probing under these conditions showed a temperature drop up to 50°C. between the cool and second-stage flames.

At high oxygen levels the heat developed by the flame causes excessive convective velocity increases along the tube axis where energy losses to the walls are minimal. The formation of the hollow cylindrical structure would seem to arise from attainment of an axial linear velocity which exceeds the burning velocity of the mixture. Cusps at its lower edge provide the necessary area to support the flame in a stable position.

The basic flow rate also has a considerable influence on the temperature at which the cool flame arises. This is shown in Fig. 4.

Tubes of 62, 42, 25 and 16 mm. internal diameter have been used successfully. At similar linear flow rates and tube temperature the principal effect of reduc-

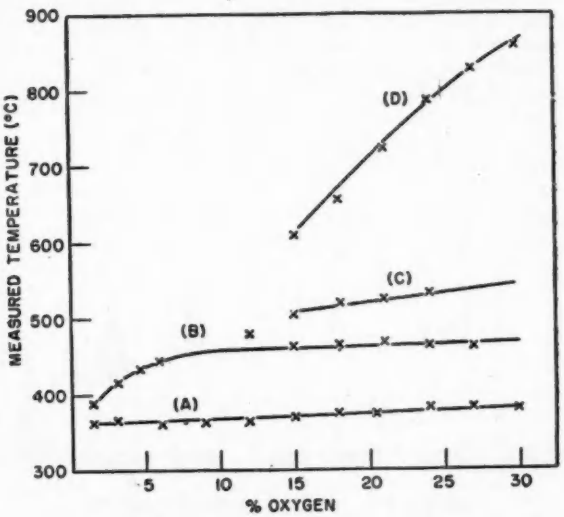


Fig. 5. Transition temperatures in flames as a function of oxygen concentration. (A) Initiation temperature of cool flame; (B) maximum temperature reached in cool flame; (C) initiation temperature of second-stage flame; (D) maximum temperature reached in second-stage flame. Basic flow 4 litres per minute. Fuel—n-hexane (15% of basic flow). Tube temperature 350°C. Tube diameter 62 mm.

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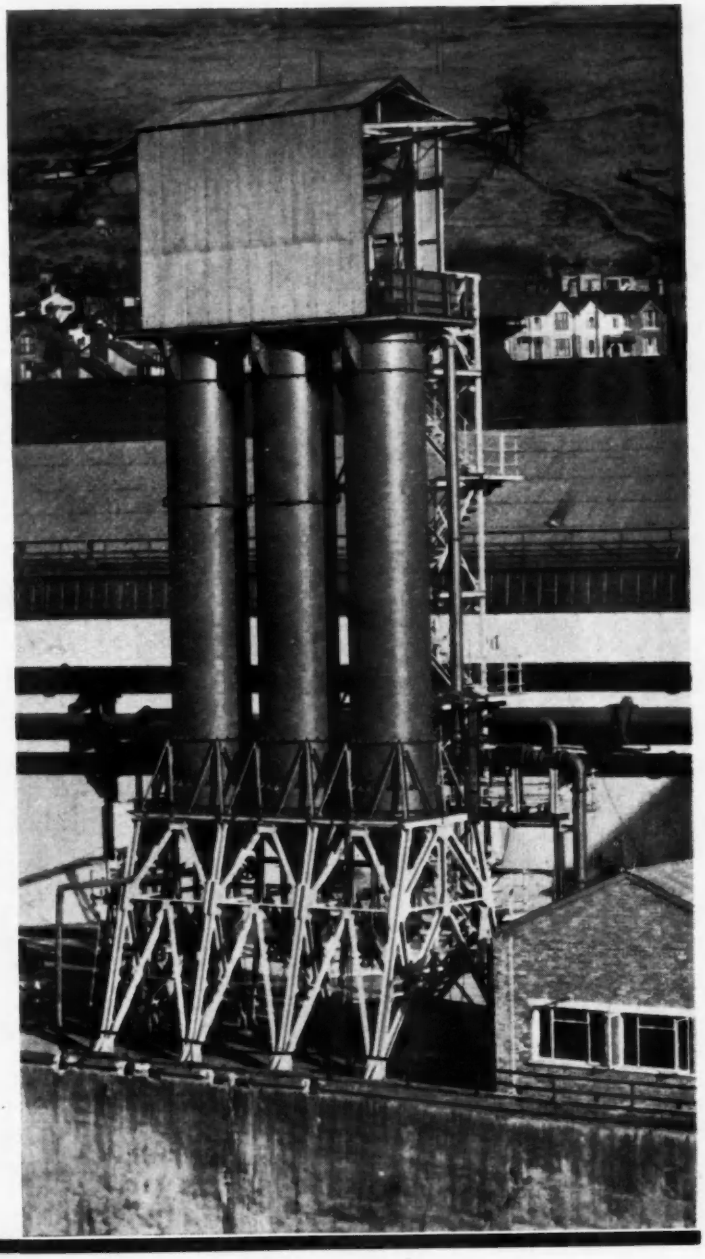

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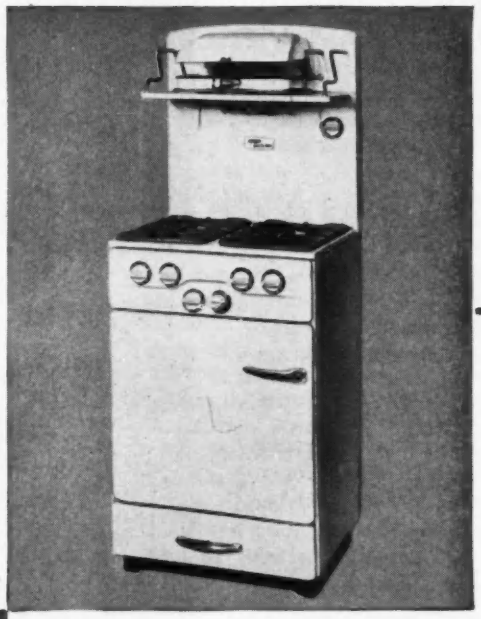

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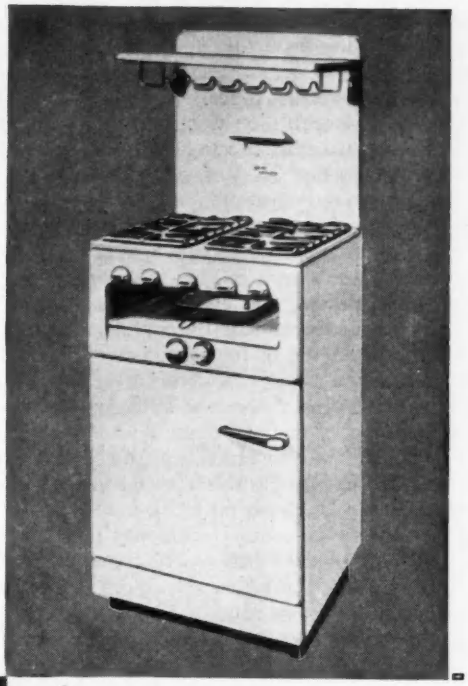

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ing the tube size was to increase the separation between the cool and second-stage flames. This effect was most pronounced in going from the 25 to the 16 mm. tube. Higher oxygen levels were required to initiate second-stage flames in the smaller tubes.

Since oxygen concentration was used as a parameter in all the studies, its gross effects on the flame structure are those shown in Fig. 3. Reduction of data relating flame the initiation temperature of the second-stage flame and the maximum flame temperature are shown in Fig. 5. The data used to plot Fig. 5 were taken from curves such as those shown in Fig. 3. Curves A and B represent the beginning and end of the steep rate of temperature rise associated with the cool flame. Curve *C* represents the beginning of the second-stage flame and curve *D* the maximum temperature observed in the tube. It may be noted in Fig. 5 that the initiation and maximum temperatures of the cool flame do not seem to be affected by the presence or absence of the second stage. Also to be noted in Fig. 6 is the fact that the maximum temperature (curve D) shows no break in the vicinity of 24% oxygen where the orange luminosity first appears.

Although most of the work reported was done with 15% *n*-hexane, a few runs were made in the 25 mm. tube at *n*-hexane concentrations of 15%, 12.5% and 10%. As the fuel concentration was reduced, no drastic variation in the cool flame was noted. On the other hand, the percentage of oxygen required for second-stage initiation increased markedly. At the same time the additional oxygen necessary to carry the flame to its point of instability decreased. Approximate limits are shown in Table 1. This relationship may account for the difficulties mentioned by Prettre[16] in establishing stable flames in upwards flow in vertical tubes. Using low fuel concentrations, the development of the second-stage flame occurs only at oxygen levels high enough to establish immediately a thermally self-sufficient flame which over-rides the controls inherent in the cool flame mechanism and propagates more or less violently downwards. Similar flame patterns were observed for

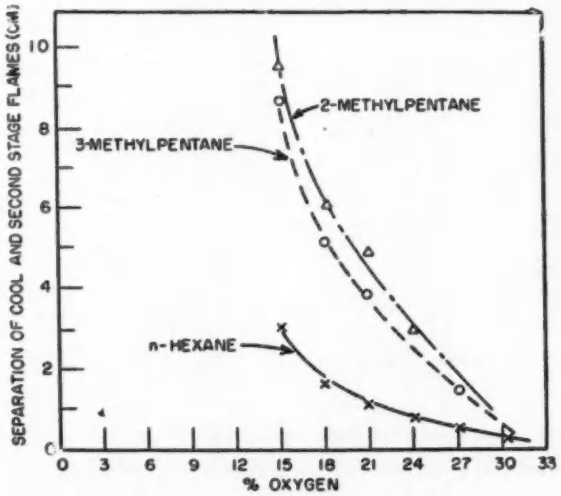

Fig. 6. Separation between cool and second-stage flames of three hydrocarbons as a function of oxygen concentration. Basic flow 4 litres per minute. Fuel—15% of basic flow. Tube temperature 350°C. Tube diameter 62 mm.

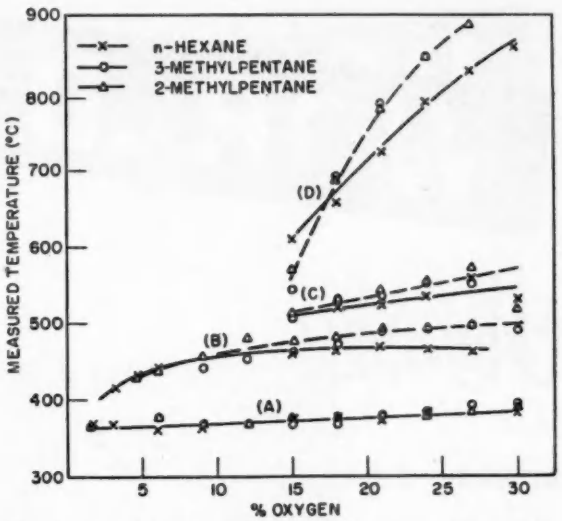

Fig. 7. Transition temperatures in flames of three hydrocarbons as a function of oxygen concentration. (A), initiation temperature reached in cool flame; (B), maximum temperature reached in cool flame; (C), initiation temperature of second-stage flame; (D), maximum temperature reached in second-stage flame. Basic flow 4 litres per minute. Fuel—n-hexane (15% of basic flow). Tube temperature 350°C. Tube diameter 62 mm.

n-hexane, 2-methylpentane, 3-methylpentane, *cyclo*-hexane and hexene-1. The separation of the cool and second-stage flames of two hexane isomers as a function of oxygen concentration is illustrated in Figure 2.

As shown in Fig. 7, the transition temperatures were similar for the hexane isomers despite the significantly different delay times. 2,3-Dimethylbutane did not ignite at tube temperatures up to 500°C. and oxygen concentrations up to 35%.

Temperature distribution within the tubes with only fuel and nitrogen flowing is characterised by the dotted line of Fig. 3. Addition of oxygen modified this pattern by cooling the lower end of the tube and heating the tube near any ensuing exothermic reactions. Because of the inverse relationship between the ignition temperature and induction delay of cool flames, the most obvious effect of tube temperature was in establishing the initial equilibrium position of the cool flame. Once a flame was established, energy transfer forwards from the combustion wave reduced the relative contribution of the tube, and beyond the transition to a thermally self-sufficient flame, the tube temperature became irrelevant.

Up to the transition point, cutting off the heater current caused the flame to migrate slowly upwards to extinction. In the case of one cool flame (4% O_2, 15% *n*-hexane) the extinction temperature was measured and found to be 278°C. Beyond the transition point the flame stabilised on the beads continued to burn indefinitely. Initial tube temperatures of 300-500°C. were employed and all permitted successful flame development. At the higher temperatures the cool flame formed well down in the tube while at lower temperatures they tended to form at the top of the tube. At low tube temperatures the cool flame initiated at temperatures

appreciably lower than those required with higher tube temperatures (see Fig. 4). The heavy deposit of soot laid down on the walls of the tube by fully developed flames (stage *F*, Fig. 2) could be removed by establishing a cool flame in the tube; 15 minutes was usually sufficient to remove all traces. Since the wall temperatures were as low as 300°C. it was believed that free radicals or some other highly reactive species were responsible. To test this qualitatively, a lead film was deposited on the outside of a test tube which was then suspended over a cool flame in the vertical reactor. Within 25 minutes the lead film had been removed.

While the experimental results attained to date provide a fertile field for speculation on the inter-relation of flame stages, the authors feel that any extended theoretical discussion of their observations should be deferred. The method is offered in its present state of development as a tool which offers certain advantages in studying the early phases of the autoignition reactions. The principal advantage of the method seems to lie in its ability to separate widely in space the stages involved in the spontaneous ignition process.

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SEVENTH INTERNATIONAL GAS CONFERENCE

IN less than a fortnight from now well over a hundred British gas men, with a hitherto unspecified number of wives, will be making their way by divers routes to Rome, where from September 25 to 28 the serious (and other) business of the International Gas Union's seventh conference will be carried on.

London in 1931 and 1949; Zurich, 1934; Paris, 1937; Brussels, 1952; New York in 1955—at least two of this year's English contingent will carry with them the happiest memories of all those previous occasions.

The work programme is very heavy; no fewer than 47 communications (they are set out below) to be presented in five two-room sessions. Our own technicians have contributed an ample share; and if we may judge from past experience, they will be relied upon in no small measure to keep alive discussions which otherwise would die.

Pre-conference tours have been arranged based on Milan and Turin, and a round tour is available for those who can stay on in the country.

Participants arrive in Rome on September 24, settle in their hotels and report at the Secretariat of the Conference at the F.A.O. Building, Viale Terme di Caracalla, which will be open from 8.30 a.m. to 5.30 p.m. (telephone: 59.00.11-59.02.11). In the afternoon there will be a sight-seeing tour, leaving at 3 p.m.

On September 25, at 11 a.m., at the F.A.O. Building, Aula Magna, there will be a welcoming speech to participants by the President of the Associazione Italiana Industriali Gas, Dott. Ing. Vittorio De Biasi. The opening ceremony of the Conference by the Minister of Industry and Commerce will follow when there will be a speech by the President of the International Gas Union, Dott. Ing. Mario Boselli. The name of the President elected for the period 1959-61 will be announced. From 3 p.m. to 5.30 p.m. at the F.A.O. Building the first section meeting will take place in the Red Room with an introduction and discussion of 'Total Gasification of Coals,' report by the Arbeitsgemeinschaft des Deutschen Gasfachs; 'Special Technical Problems Arising from the Transport of Gas Manufactured at Long Distances and at High Pressure,' report by the Association Technique de l'Industrie du Gaz en France; 'Survey of the Development of the Use of Petroleum Products in Town Gas Manufacture,' report by the Institution of Gas Engineers; 'Telemetering Control and Automation in Gas Pipeline Operation,' Ir. N. H. M. Tychon.

Also, in the Green Room, the second section meeting will take place with an introduction and discussion of 'International Statistics of the Gas Industry,' report by the Association Royale des Gaziers Belges; 'Safety Regulations for the Prevention of Gas Explosions,' G. Rasmussen; 'Two Years of Experience on the Different Uses of Residual Refinery Gases at the Gasworks of Naples,' Dott. Ing. D. E. Galanti; 'The Application of Chemical Engineering Principles to the Cooling and Purification of Town Gas,' G. Dougill and E. Spivey. In the evening, at 6.15 p.m., there will be a visit to the

Capitol, where participants will be received by the Mayor of Rome.

On September 26, from 9 a.m. to 12.30 p.m., at the F.A.O. Building the first section meeting in the Red Room will comprise an introduction and discussion of 'Use of Coke for Central Heating in Automatic Boilers,' report by the Société Suisse de l'Industrie du Gaz et des Eaux; 'Measures to Be Taken in Gasworks and Coking Plants Against Pollution of the Atmosphere by Dust, Smoke, Vapour, Odours, Poisonous or Corrosive Gases,' report by the Association Technique de l'Industrie du Gaz en France; 'Tariff Techniques at the Service of the Expansion of the Gas Industry,' G. Robert and A. de Saint-Vincent; 'Co-ordinated Industry Promotion and Advertising,' Chester S. Stackpole; 'Consumption Statistics per Consumer and per Appliance—Considerations on Recording Methods,' Dott. Ing. A. Böhm. In the Green Room the second section meeting will be held comprising introduction and discussion of 'Report by the International Committee for the Harmonisation of Essential Clauses in the Specifications for Stamping of Domestic Gas Appliances'; 'The Economic Importance of Natural Gas and its Use in Austria,' Dipl. Ing. E. Klement; 'Methods and Procedures of Analogical Calculation for Gas Transmission and Distribution Systems,' A. Renauldon; 'Role of the Scientific Research in the Evolution of Town Gas Industry,' Prof. G. Malquori; 'Observations on the corrosion of underground pipelines,' R. de Brouwer. For the ladies, from 9 a.m. to 12.30 p.m., there will be a visit to the Galleria Borghese and four Rome basilicas.

Ignition Safety Devices

In the afternoon, from 3 p.m. to 6.30 p.m., the programmes will be: Red Room, first section meeting—introduction and discussion of 'Ignition Safety Devices on Domestic Gas Appliances,' report by the Arbeitsgemeinschaft des Deutschen Gasfachs; 'Effects of the Rapidly Expanding Use of Gas for Winter Heating on Service Efficiency and Safety; Measures Taken and Experience Acquired,' report by the Associazione Nazionale Industriali Gas'; 'Different Methods Used to Meet Gas Peak Loads, with Particular Reference to the Use of Natural Gas, Oil and Liquefied Petroleum Gas,' Ing. F. Schüssl; 'New Methods for Distribution Design,' George S. Young, 'The Distribution of Straight Natural Gas at 300 mm. (12 in.) w.g.,' Ir. D. Tinbergen. In the Green Room, second section meeting—introduction and discussion of 'First Aid and Artificial Respiration. Training Programme and General Instructions for Personnel in the Gas Industry,' report by the Svenska Gasverksföreningen; 'Developments in Methods of Gas Measurement, particularly of Large Volumes of Gas at High Pressure,' report by the Institution of Gas Engineers; 'The Use of Plastic Materials in Gas Meter and Regulator Diaphragms,' C. J. Sevey and J. Stanford Setchell; 'Civil Engineering in the Gas Industry—Recent Developments,' D. A. Andrews; 'Studies and Researches on the Production of Town Gas by Chemical Conversion of Hydrocarbons,' Pro. C. Padovani. At 9 p.m. there will be a dinner and dance at the Excelsior Hotel (evening dress).

On September 27, from 9 a.m. to 12 p.m., at the F.A.O. Building, in the Red Room the first section meeting will comprise an introduction and discussion of 'Investigation on Unconventional Flues,' report by The Institution of Gas Engineers; 'Survey of Modern Methods Used in the Physical and Chemical Processing of Gas in Coking Plants,' report by the Association Technique de l'Industrie du Gaz en France; 'The Supply of Gas to the City of Hamburg on the Basis of Coal Gas, Refinery Tail Gases and Natural Gas, Combined with an Underground Storage,' Direktor Dipl. Ing. G. Düwel; 'The Putting into Operation of Spherical Gasholders and Some Technical Properties of Gaseous Flows,' Prof. Dr. Ing. F. Schuster; 'Fuel Gasification and Gas Conversion. A new Method (with Formulae and Coefficient Tables) for the Calculation of the Composition of Gaseous Equilibrium and of the Reaction Temperatures,' Prof. H. Deringer. In the Green Room the second section meeting will comprise an introduction and discussion of 'Report by the Committee for the Study of New Gas Distribution Techniques,' 'The Use of Plastic Material for Mains and Service Pipes,' report by the Vereniging Van Gasfabrikanten in Nederland; 'Underground Storage of Gas in France,' R. Delsol; 'Principles of Instrumentation and Automatic Control on a New Gasworks,' J. E. Davis and T. A. Lucas; 'Odour and Odorisation of Gases,' Dott. Ing. Mario Sales.

Danger in Cold Weather

In the afternoon, from 3 p.m. to 6 p.m., in the Red Room the first section meeting programme will comprise an introduction and discussion of 'Survey of Difficulties, Damage and Danger to a Supply System During the Coldest Winter Season; Remedial Measures,' report by the Associazione Nazionale Industriali Gas; 'Economics of High B.t.u. Oil Gas,' Hall M. Henry; 'Considerations and Experiences on the Static of Gasholder Crowns,' Dott. Ing. Mario Boselli; 'Plastometric Method Experiences at the Coke Oven Plant of the Basel Gasworks,' W. Devecchi. The Green Room, second section meeting, will comprise an introduction and discussion of 'New Technique for Reconditioning Old Natural Rubber Joints in Distribution Networks—Study of the Composition of Rubber Joints and of Control Tests,' report by the Association Royale des Gaziers Belges; 'Problems Connected with the Odorisation of Different Types of Gas for Public Supply,' report by the Associazione Nazionale Industriali Gas; 'Flame Stability and the Interchangeability of Gases,' Ir. J. C. Theron Mulder and Prof. Dr. D. W. van Krevelen; 'The Optimum Economics of a Supply with a Mixture of Different Gases,' H. A. A. de Melverda.

At 4.30 p.m., for the ladies, there will be a tea and fashion-show at the Grand Hotel, offered by Mrs. Vittorio De Baisi. At 6.15 p.m ., at the F.A.O. Building, Aula Magna, will take place the closing of the Conference; while at 2 p.m. there will be a concert at the auditorium of RAI—Radiotelevisione Italiana—by invitation.

On September 28 there will be a car excursion to the Castelli Romani leaving at 8 a.m. It is hoped that the Pope will grant an audience to participants at Castelgandolfo. A luncheon will be given by the Società Italiana per il Gas (Esercizio Romana Gas), followed by a visit to the Villa d'Este, Tivoli.

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The "Gas Journal" is published every Wednesday, price 1/6d.; by post 1/9d.

Subscription Rates: Home 65/–; Overseas (from Sept. 1, 1957) 72/6 per annum; (Both payable in advance.) A copy of the "Gas Journal" Calendar & Directory is presented each year to continuous subscribers.

Classified Advertisements: All small classified advertisements are charged at 2/6 per line (approx. 7 words)—minimum charge 10/–. A Box Number address occupies 2 lines, and a further 6d. is charged towards cost of postage on replies. Copy must be received by first post on Monday to ensure insertion in that week's journal.

Displayed Advertisements: Rates obtainable on application to the Business Manager. Change of copy for displayed spaces must be received 14 days prior to publication if proofs are required. Type area of inside pages 10 in. deep × 7 in. wide; block screen 120.

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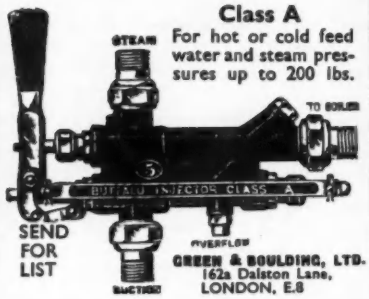

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PATENTS AND TRADE MARKS

THE Proprietors of British Patent No. 729,265 for "IMPROVEMENTS IN AND RELATING TO GAS PURIFIERS," desire to enter into negotiations with a firm or firms for the sale of the patent or for the grant of licences thereunder. Further particulars may be obtained from Marks & Clerk, 57 & 58, Lincoln's Inn Fields, London, W.C.2.

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PUBLIC NOTICE

Kings Langley Engineering Co., Ltd., Herts.
James H. Lamont & Co. Ltd., Edinburgh.

WE, Kings Langley Engineering Co. Ltd., hereby publish, at the request of James H. Lamont & Co. Ltd., an apology for having in our circular under Refs. KVS/E-KVS/G and KVS/ROS entitled "Kingley" Copper Tube Fittings issued during March, 1958, made use of the trade mark "Securex" belonging to James H. Lamont & Co. Ltd., and of extracts from their Trade Catalogue in respect thereof.

APPOINTMENTS VACANT

ASSISTANT to Works Physicist required, with knowledge of Gas Appliance Industry. Write stating age, details of qualifications, experience and salary required. Box No. 345, *Gas Journal*, 11, Bolt Court, E.C.4.

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Applications, giving details of age, qualifications and experience, together with the names of two referees, should be addressed to the Industrial Relations Officer, West Midlands Gas Board, 6, Augustus Road, Edgbaston, Birmingham, 15, **to reach him not later than September 27, 1958.**

J. SWAN,
Secretary to the Board.

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MESSRS. SIDNEY FLAVEL & CO., of Leamington Spa have a vacancy in their research laboratories for a physicist or chemist, with experience in the testing and development of gas appliances, and particularly of water heaters and space heaters. Apply giving particulars of experience and salary required, to the Technical Director.

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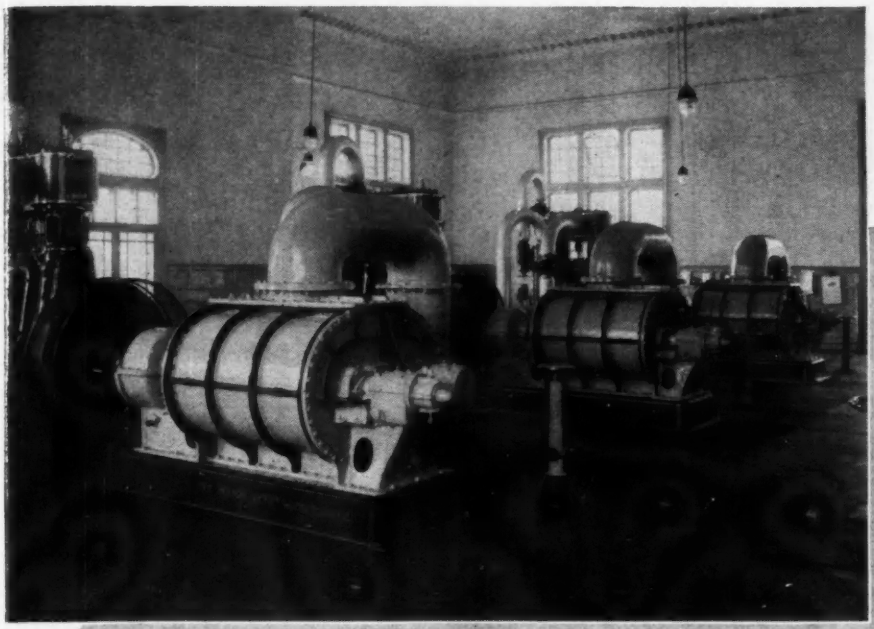
D. A. FOSTER.
Group Manager.



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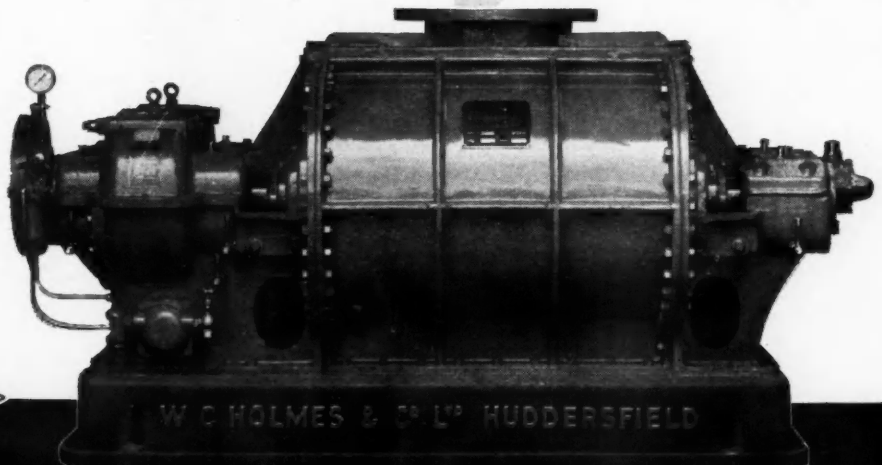

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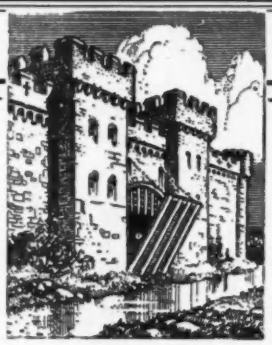

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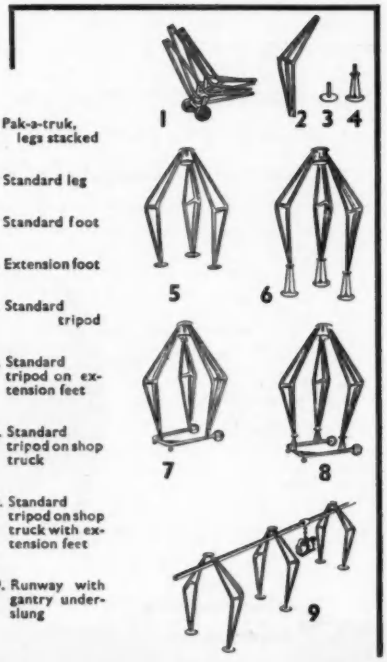

1. Pak-a-truk, legs stacked
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3. Standard foot
4. Extension foot
5. Standard tripod
6. Standard tripod on extension feet
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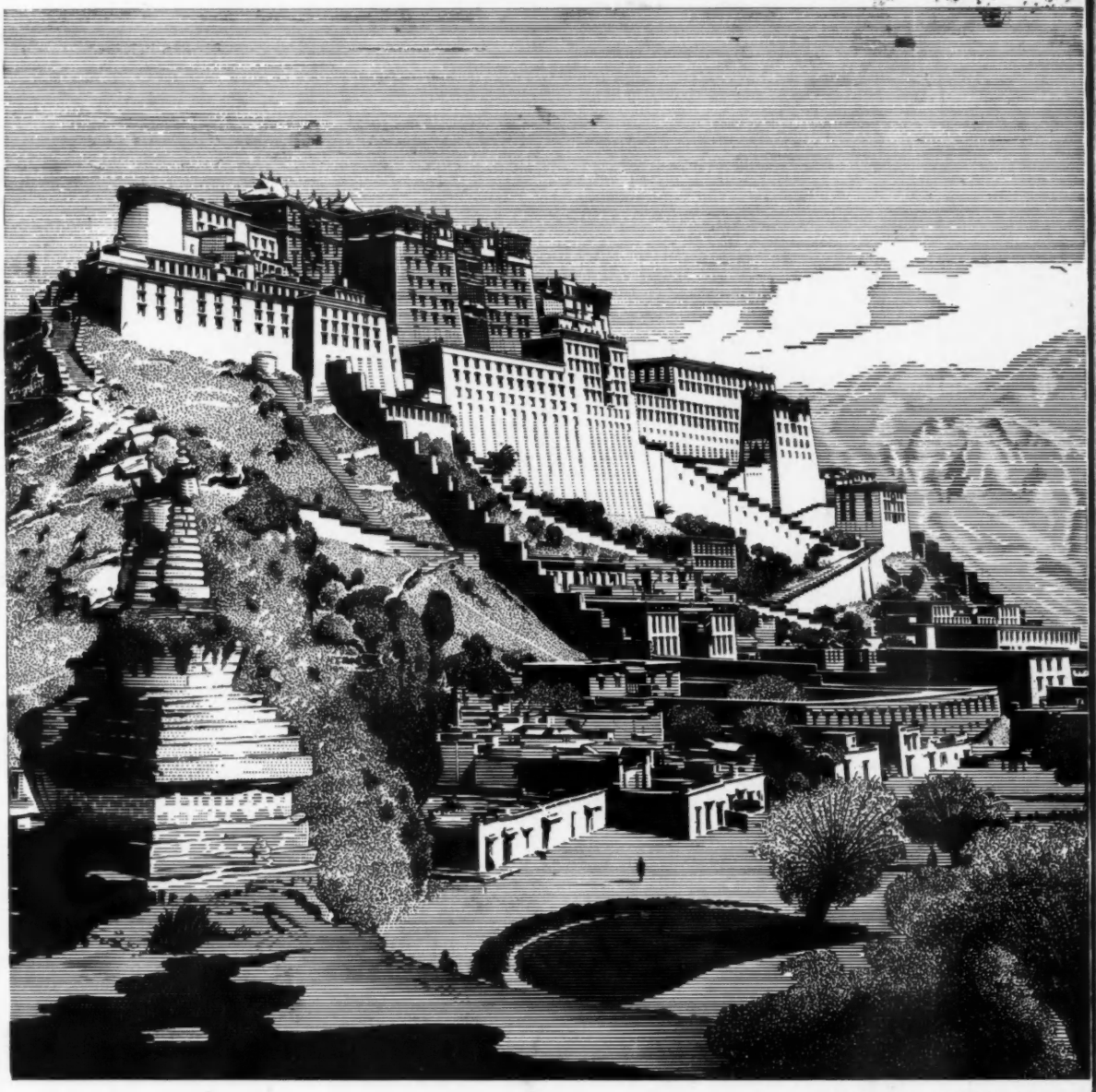

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